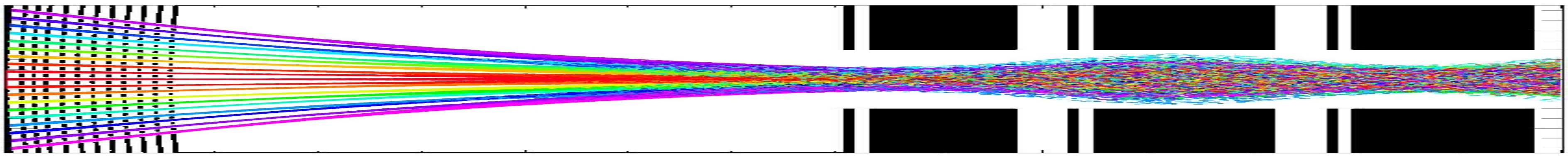
Key question in Heavy Ion Fusion beam science:

How do intense ion beams behave as they are accelerated and compressed into a small volume in space and time?



Simulation of space-charge-dominated ion beams plays a major role in developing the answers

Alex Friedman, LLNL & LBNL

OFES Remote Theory Seminar
July 13, 2004

BERKELEY LAB
PPPL
PRINCETON PLASMA PHYSICS LABORATORY
Heavy Ion Fusion
Virtual National Laboratory

Outline

I. Introduction

II. Present-day experiments

III. Fundamental beam science

IV. Future experiments & discussion

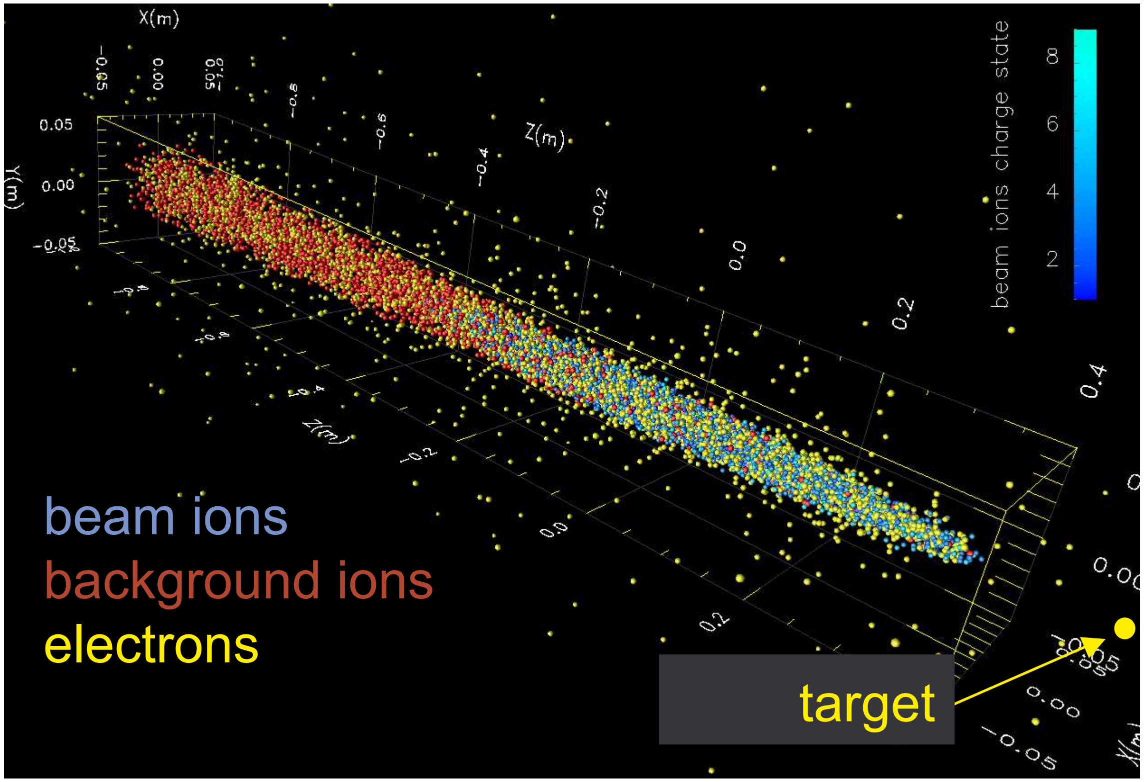
… and along the way …

New computational methods and models that have broad applicabilty

Beams are non-neutral plasmas with dynamics dominated by long-range space-charge forces

They are collisionless and have "long memories" — must follow ion distribution from source to target

Beam modeling program is
~ 2/3 simulation,
~ 1/3 analytic theory;
here we discuss the former

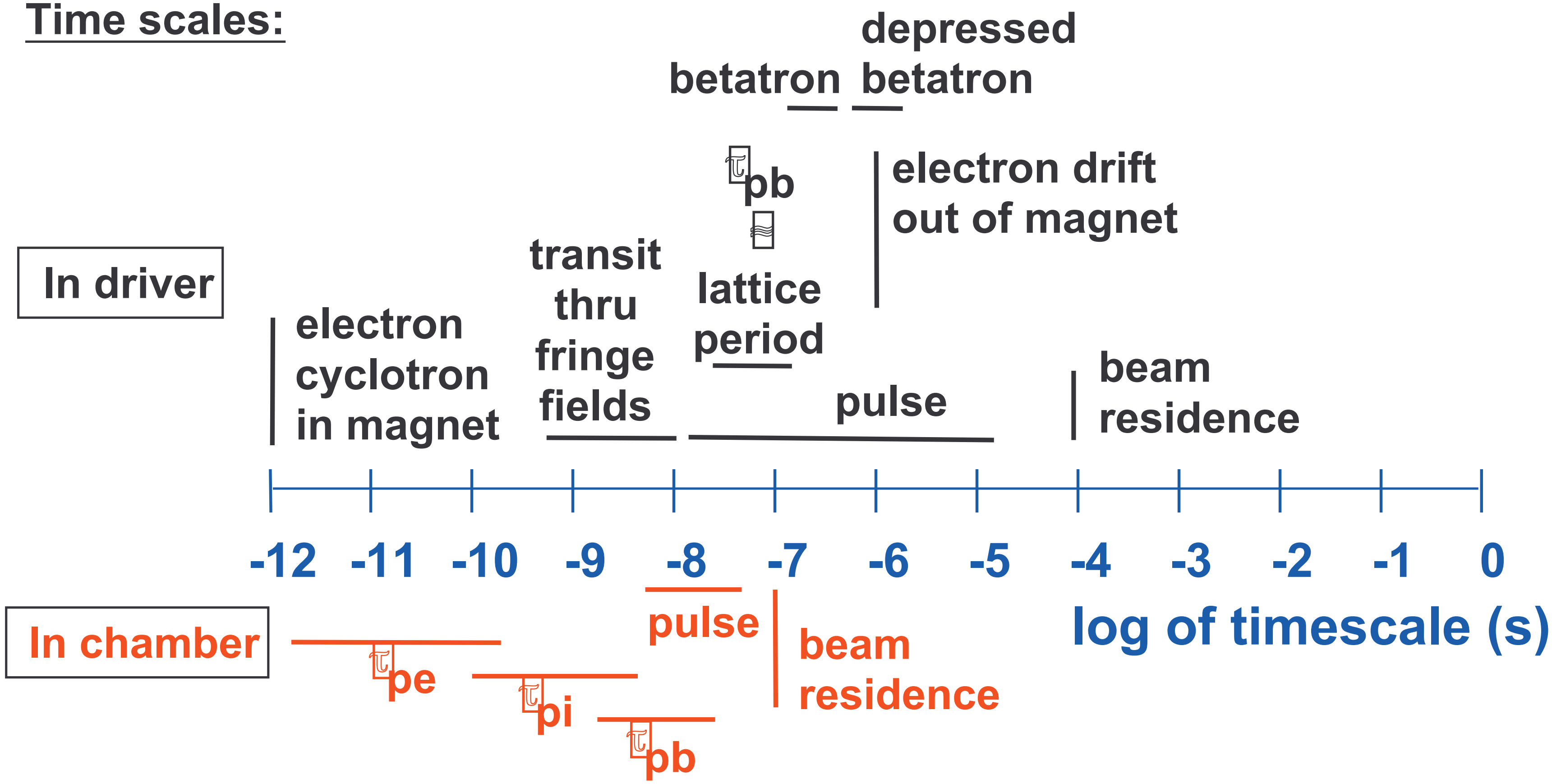


"Multiscale, multispecies, multiphysics" - ions encounter:

- **Good electrons**: neutralization by plasma aids compression, focusing
- **Bad electrons**: stray "electron cloud" and gas can afflict beam

Time and length scales in driver and chamber span a wide range

Time scales:



Length scales:

- electron gyroradius in magnet ~ 10 μm
- $\lambda_{D,beam}$ ~ mm
- beam radius ~ cm
- lattice period ~ m
- beam length ~ 1-10 m
- machine length ~ km

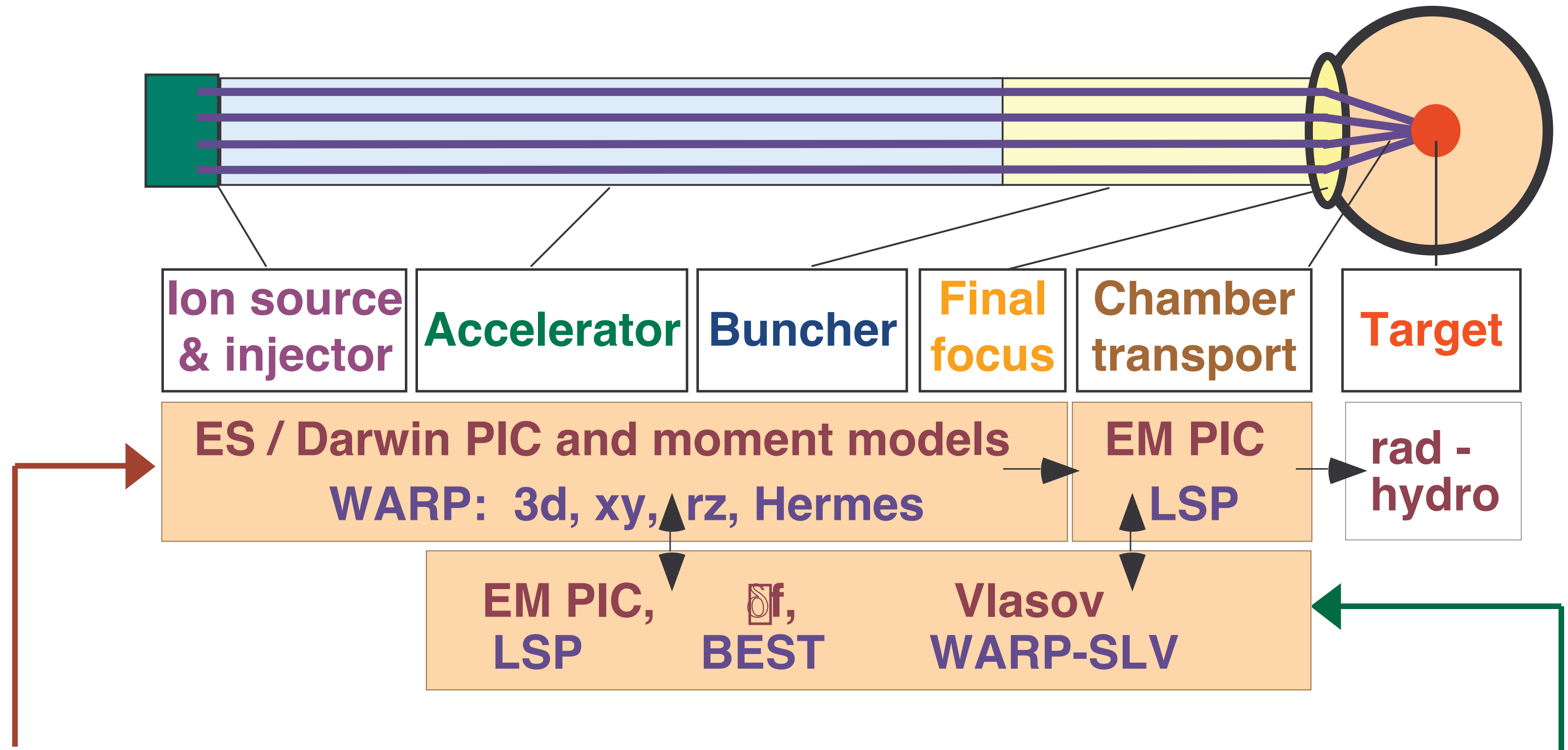
Beam starts with a small 6D phase space volume; applications demand that it grow only modestly

- Present-day (*e.g.*, "HCX") beams, roughly:
  - Total ions N ~ 5 x 10^{12} (K^+) in ~ 5 μs (0.2 Amperes)
  - line charge density λ ~ 0.1 μC/m
  - number density n ~ 10^{15} m^{-3}
  - kinetic energy E_k ~ 1 MeV (v/c ~ 0.005)
  - temperature T_{eff} ~ 0.2 eV at 5-cm source,
    ~ 20 eV in transport section
  - beam radius r ~ 1 cm
- T and r translate to initial transverse phase space area ("normalized emittance") ~ 0.5 π-mm-mr
- Downstream, in a 2-GeV driver:
  - λ increases ~ 5x in accelerator, then 20x in final compression
  - Have "headroom" for phase space area to grow by ~ factor of 10 (less is always better)

Particle-in-Cell (PIC) is main tool; challenges are addressed by new computational capabilities

- resolution challenges (Adaptive Mesh Refinement-PIC)
- dense plasmas (implicit, hybrid PIC+fluid)
- short electron timescales (large-Δt advance)
- electron-cloud & gas interactions (new "roadmap")
- slowly growing instabilities (δf for beams)
- beam halo (advanced Vlasov)

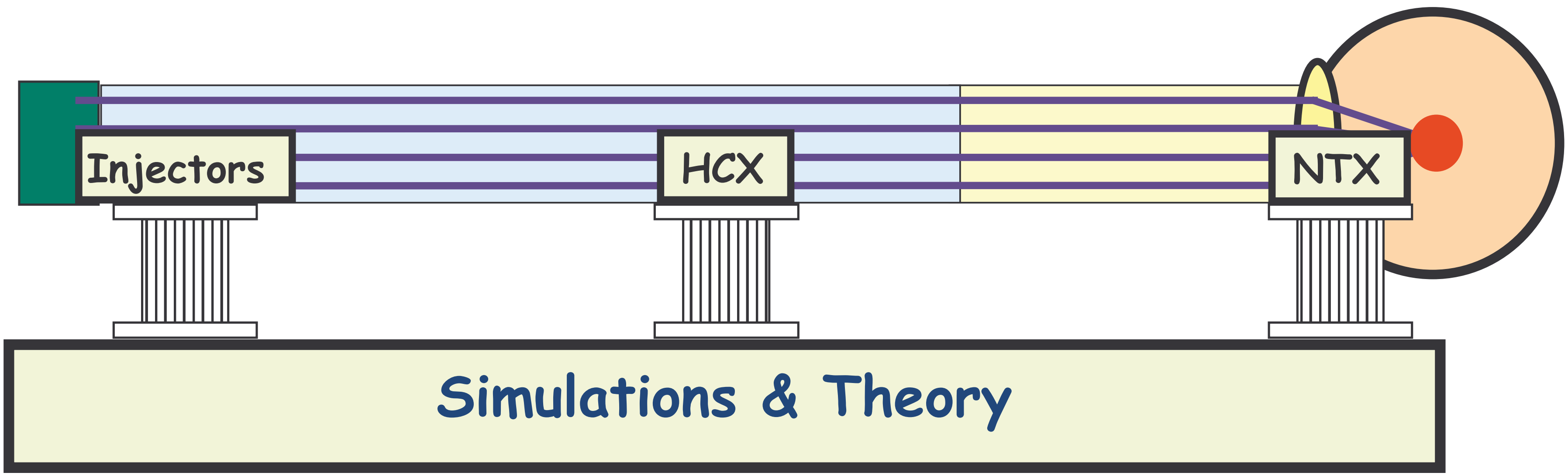
HIF-VNL's approach to self-consistent beam simulation employs multiple tools



Track beam ions consistently along entire system

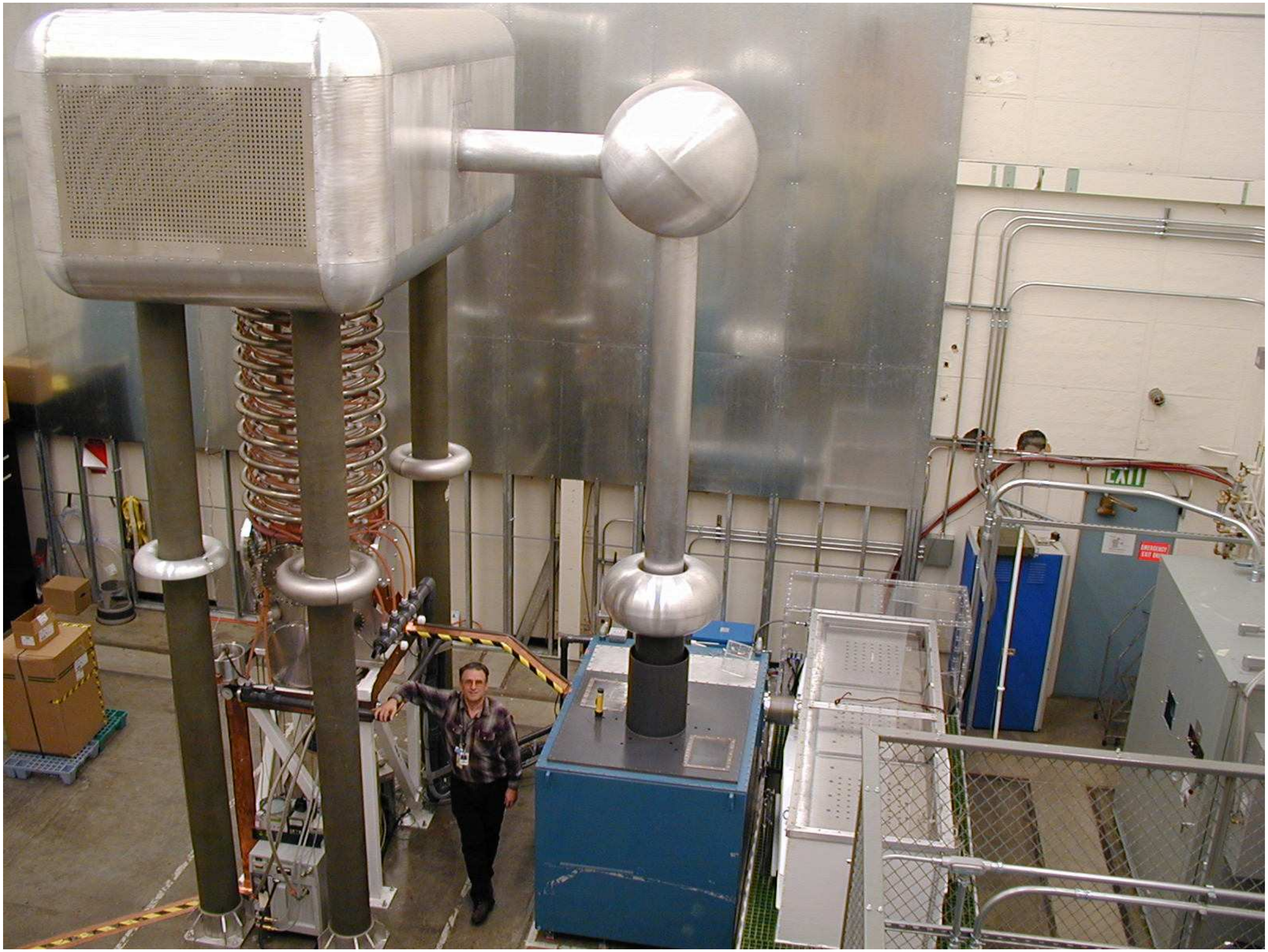
Study instabilities, halo, electrons, ..., via coupled detailed models

II. Simulations and theory support present-day ion beam experiments



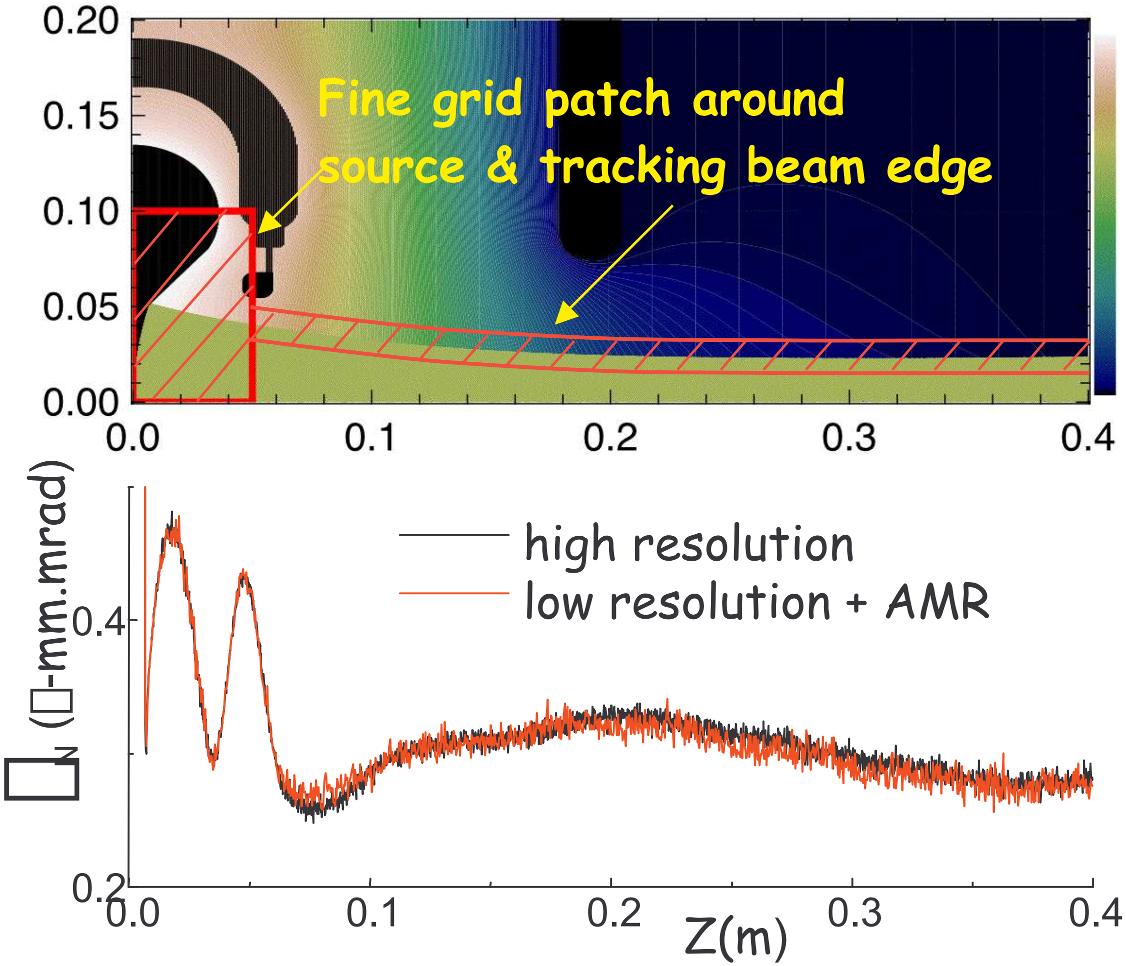
Injectors

Research on high-brightness sources & injectors uses test stands, including STS-500 at LLNL



Particle simulation & adaptive mesh refinement (AMR) are married at last!

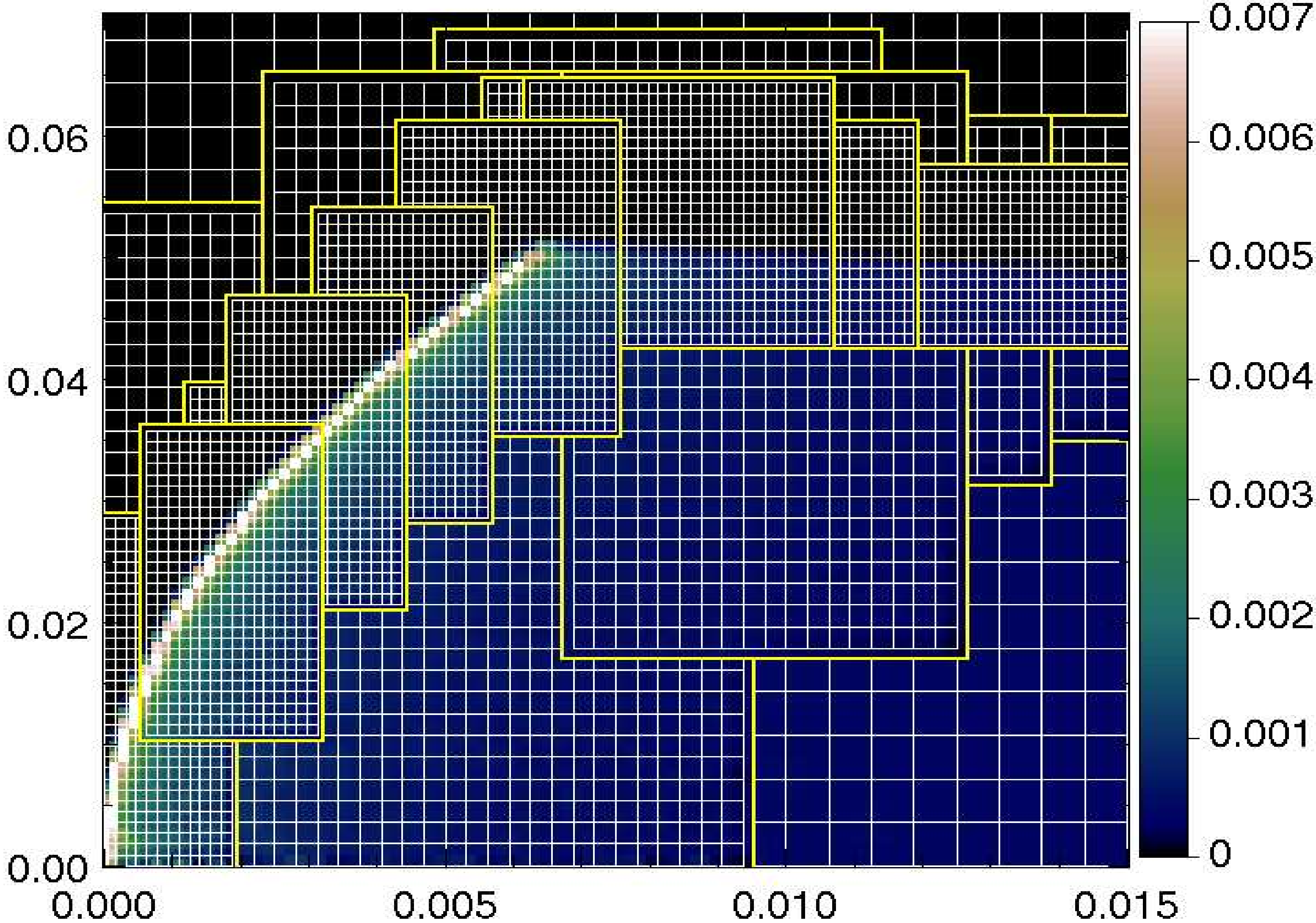
Application to HCX triode in axisymmetric (r,z) geometry



This example:
~ 4x savings in computational cost
(in other cases, far greater savings)

(Simulations by J-L. Vay)

Adaptive Mesh Refinement requires automatic generation of nested meshes with "guard" regions

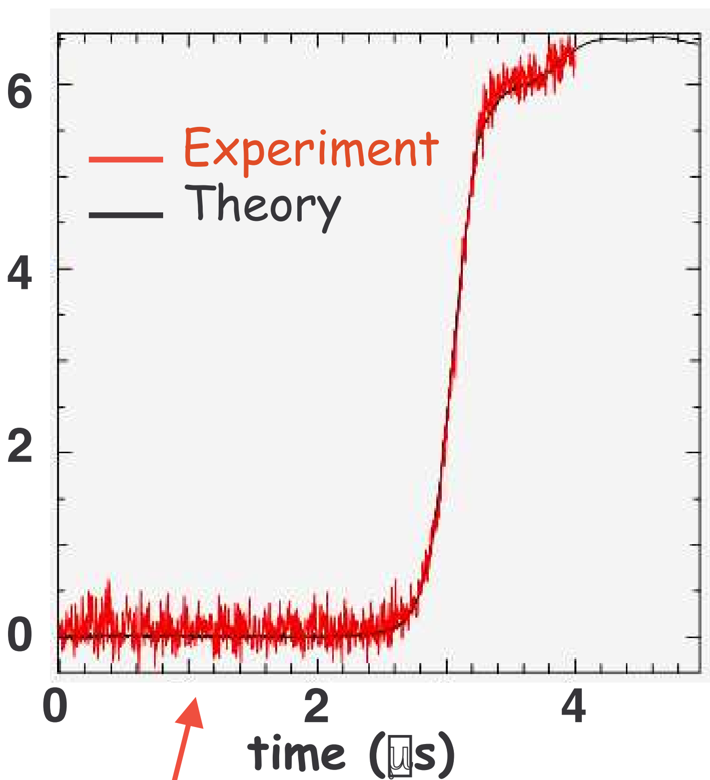


Simulation of diode using merged Adaptive Mesh Refinement & PIC

WARP simulations of STS-500 experiments significantly advance the state of the art

Rise time

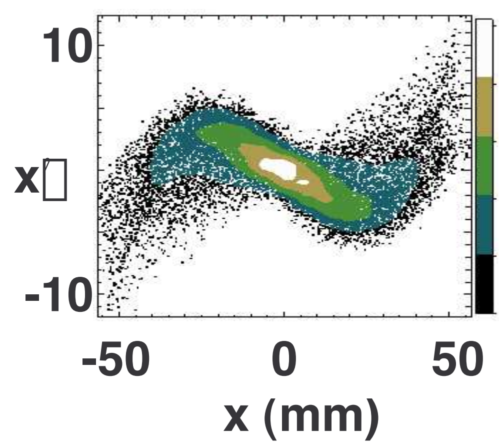
Current (mA) at Faraday cup



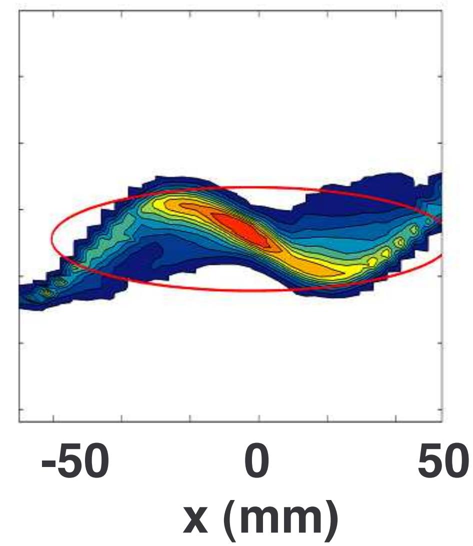
Result depends critically on mesh refinement

Phase space at end of diode

Warp simulation



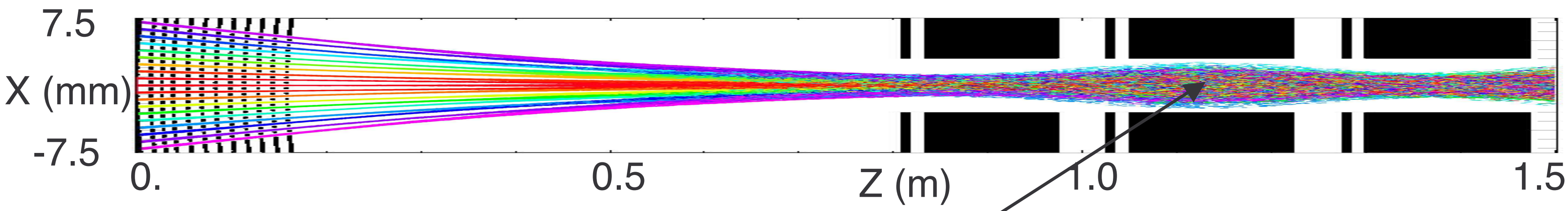
Experimental data



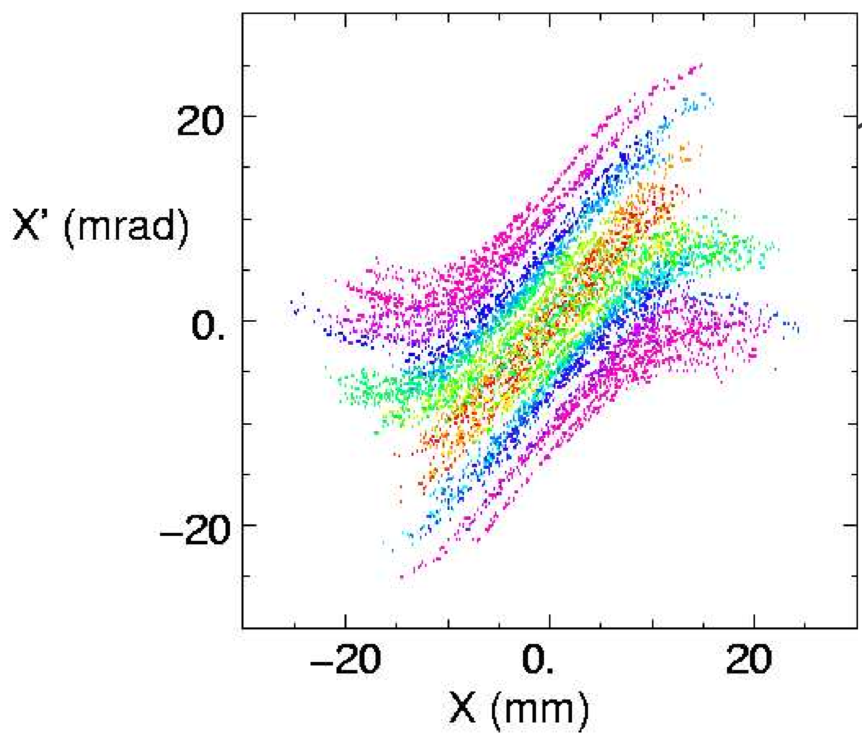
5-cm-radius K^+ alumino-silicate source

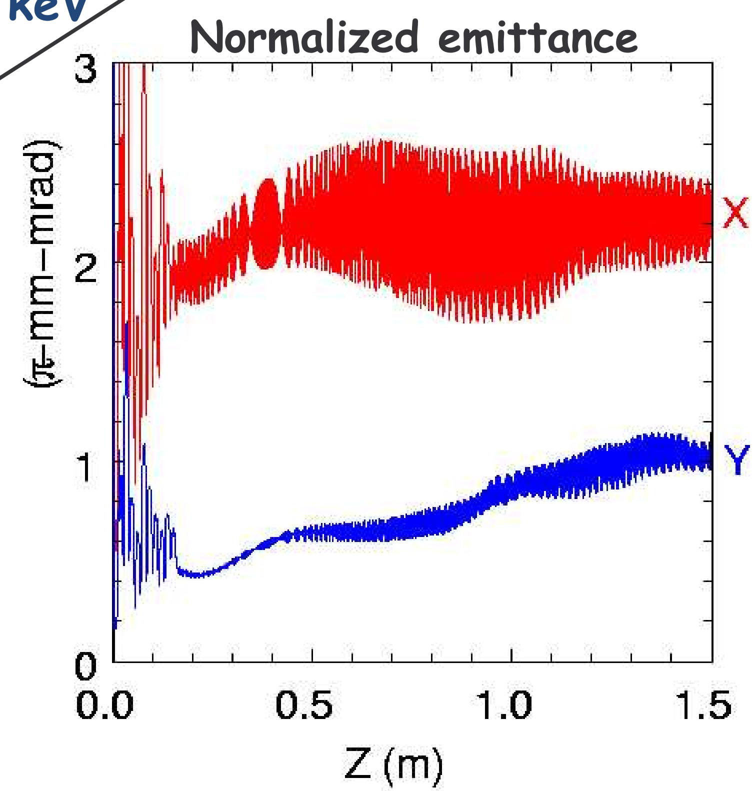
(Simulations by I. Haber, J-L. Vay, D. P. Grote)

WARP simulations guided the physics design of the beamlet-merging experiment on STS-500



119 beamlets, I_{Total} = 0.07 A, E_{final} = 400 keV





RZ and XY for synthesis; 3D for validation

(Simulations by D. Grote)

HCX

The High Current Experiment enables studies of beam dynamics and stray-electron physics

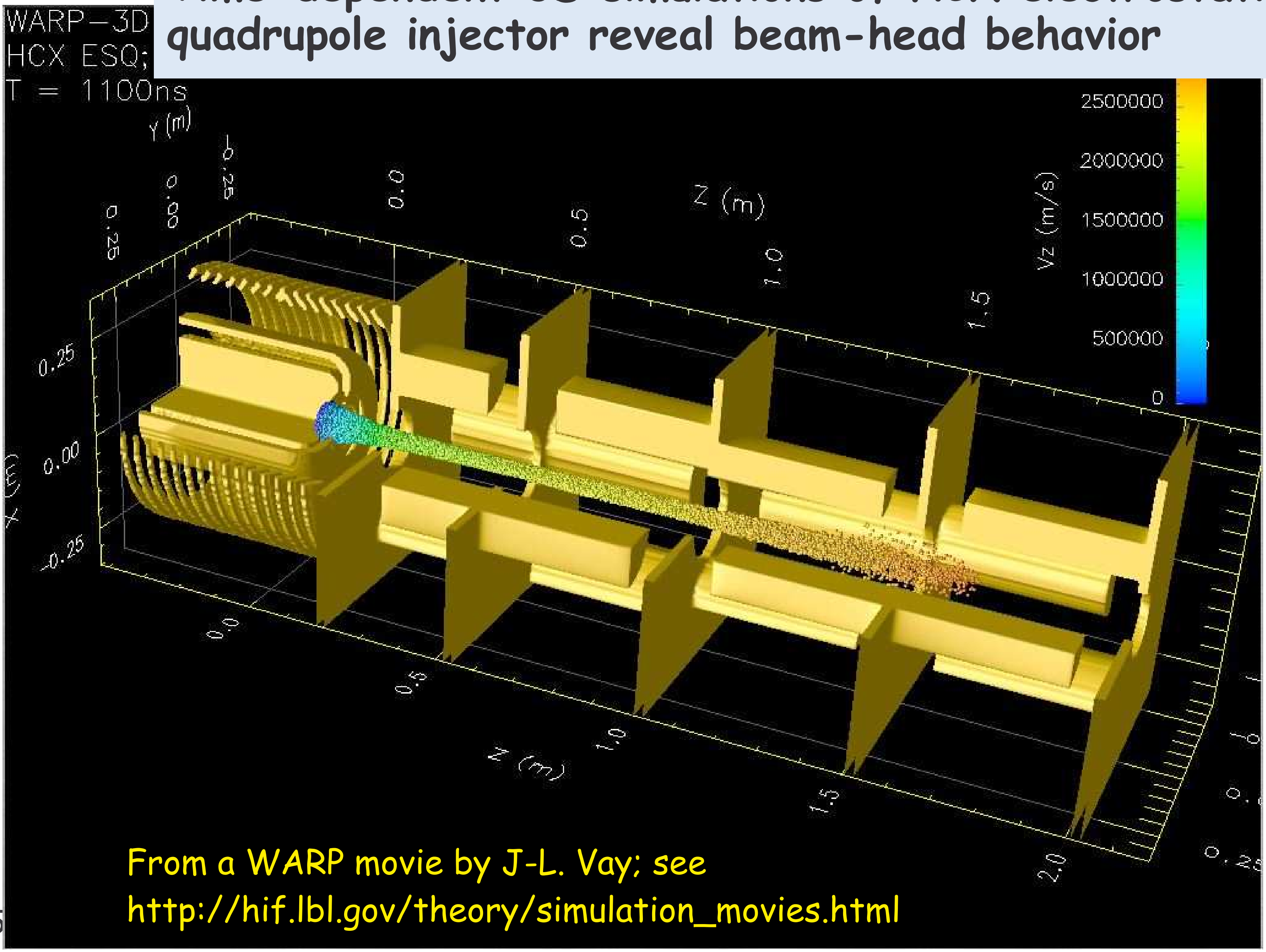
K^+ Beam

~ 0.2 - 0.5 A

1 - 1.7 MeV

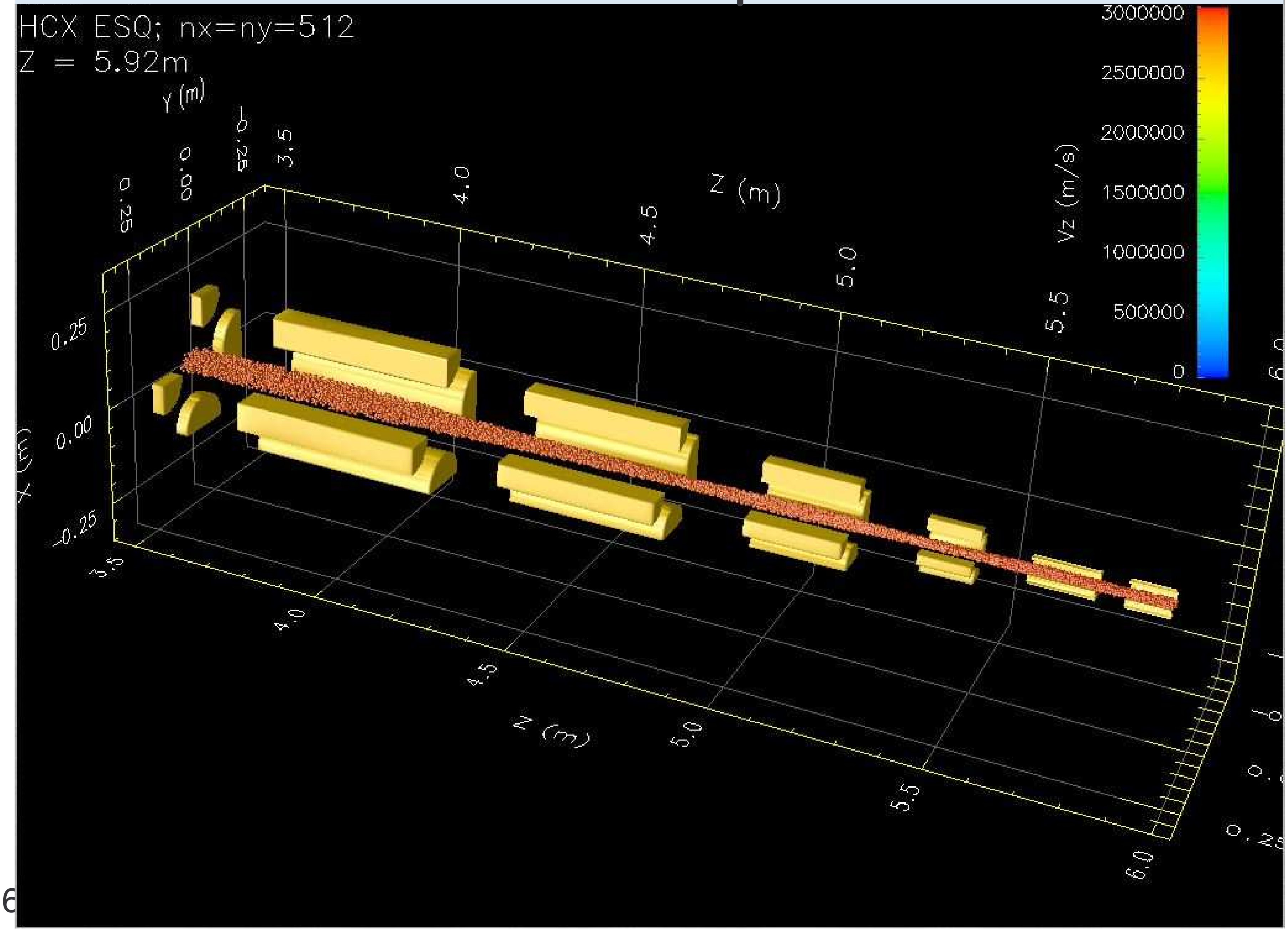
~ 5 μs

Time-dependent 3D simulations of HCX electrostatic quadrupole injector reveal beam-head behavior

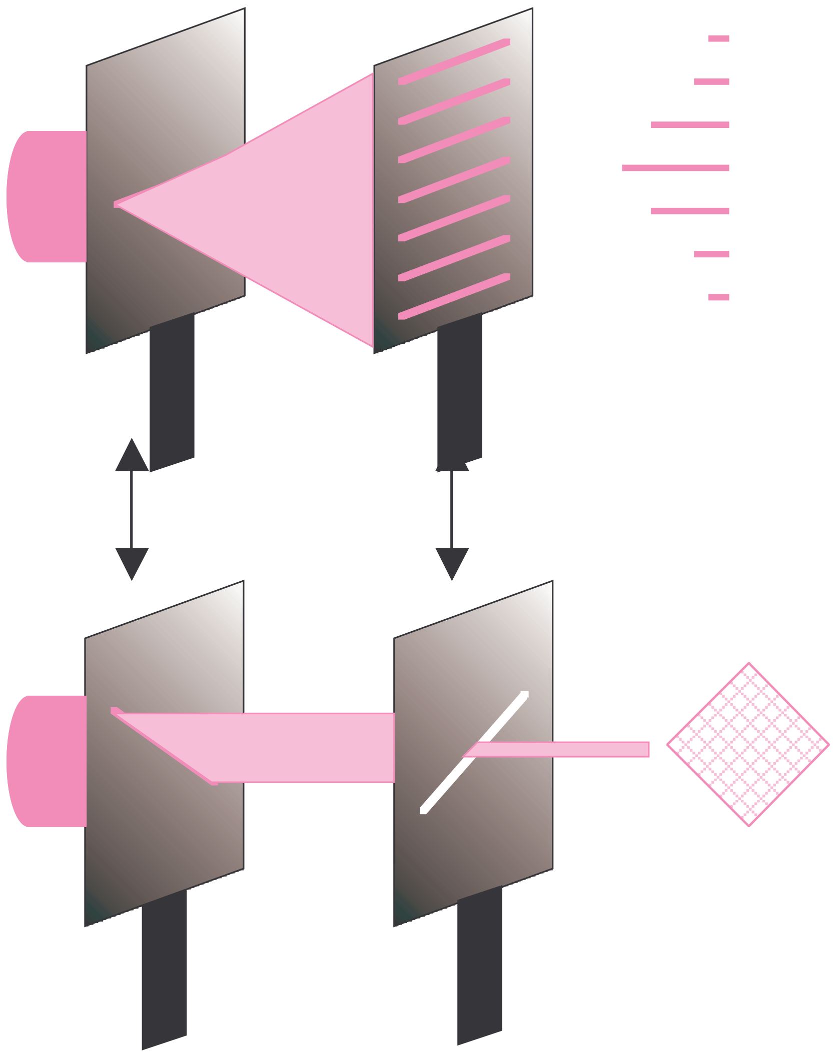


From a WARP movie by J-L. Vay; see
http://hif.lbl.gov/theory/simulation_movies.html

Matching section compresses beam significantly before it enters the HCX transport line



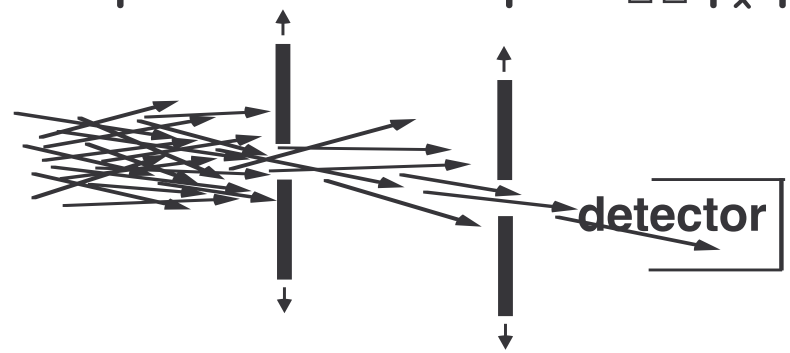
A common experimental diagnostic is based on slit-scanners



Two-Slit Emittance Scan:
Measures the beam phase space projection perpendicular to the slits:

slit 1 selects for position x

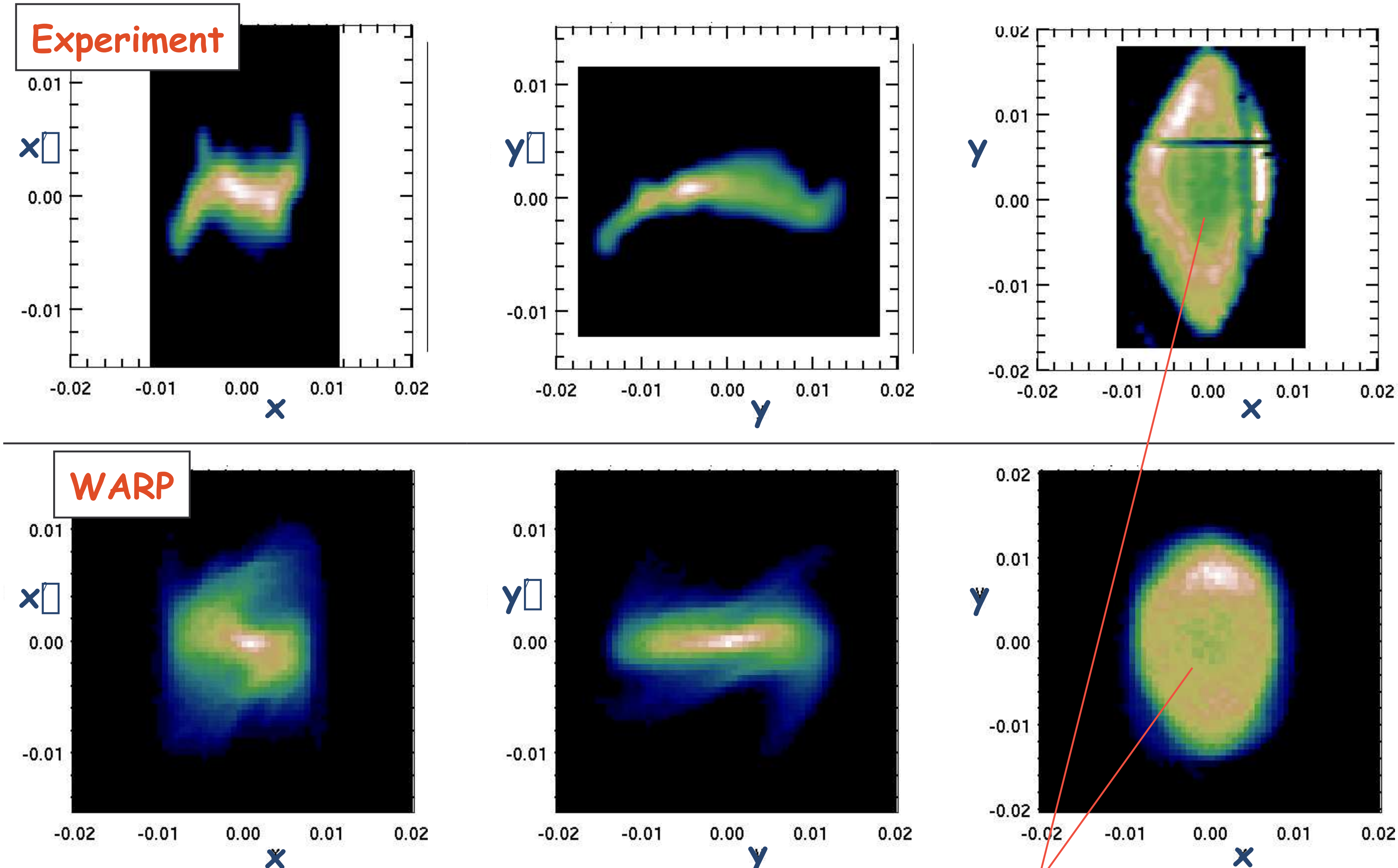
slit 2 selects for "slope" $x' \approx p_x/p_z$



Crossed-Slit Intensity Map:
Measures the distribution of beam current density in the transverse plane

The 4D distribution $f(x,y,x',y')$ is not uniquely determined by a small number of such 2D scans; "synthesize" an f tomographically

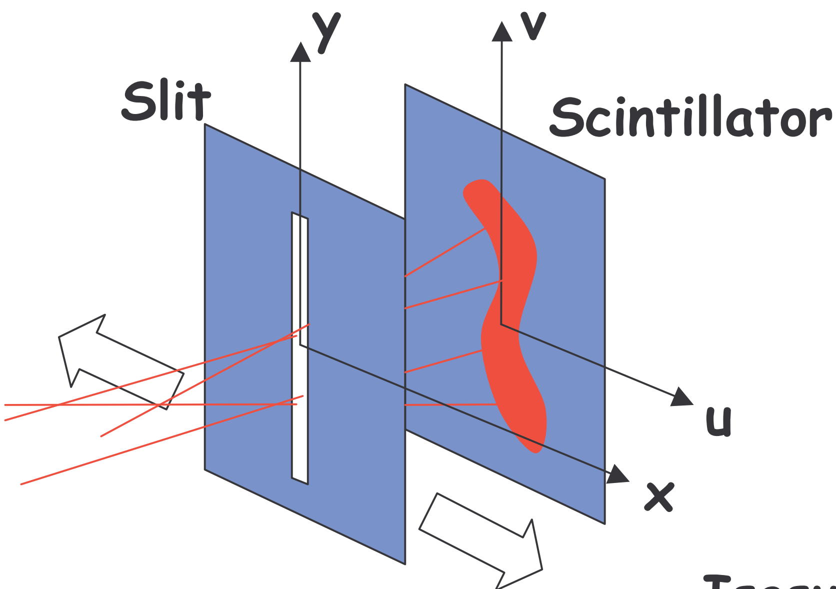
Some HCX runs use initial conditions derived from slit-scan data



Simulations initialized this way agree only roughly w/expt ⇒ need better data

Hollowing is a common feature (Simulations by C.Celata)

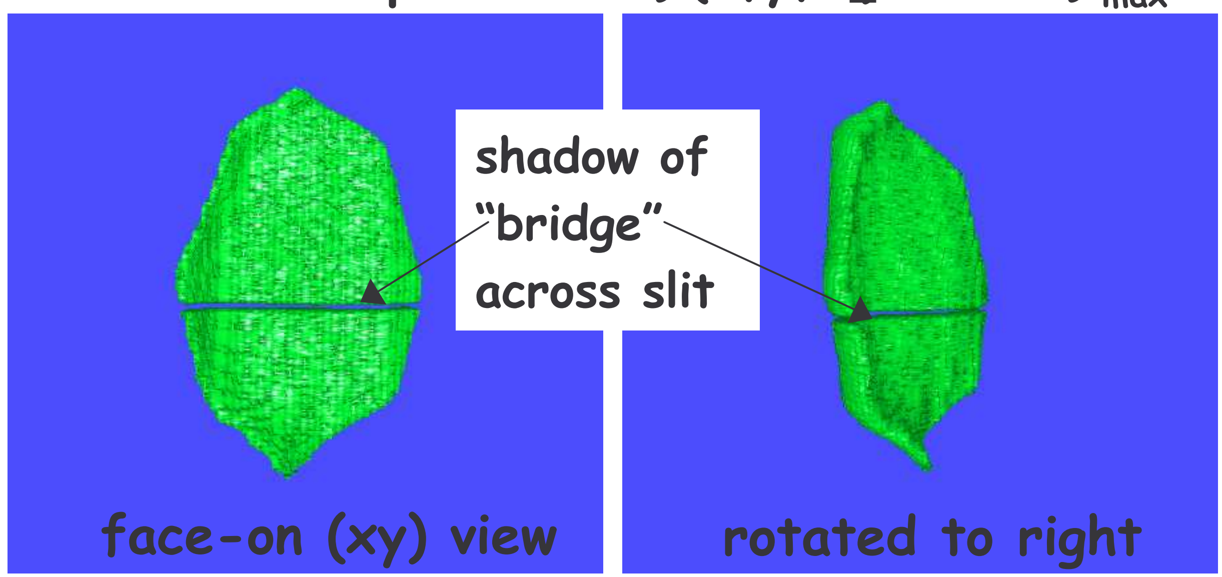
"Optical slit" diagnostic is yielding unprecedented information about the HCX beam particle distribution



This scanner measures f(x,y,x′)

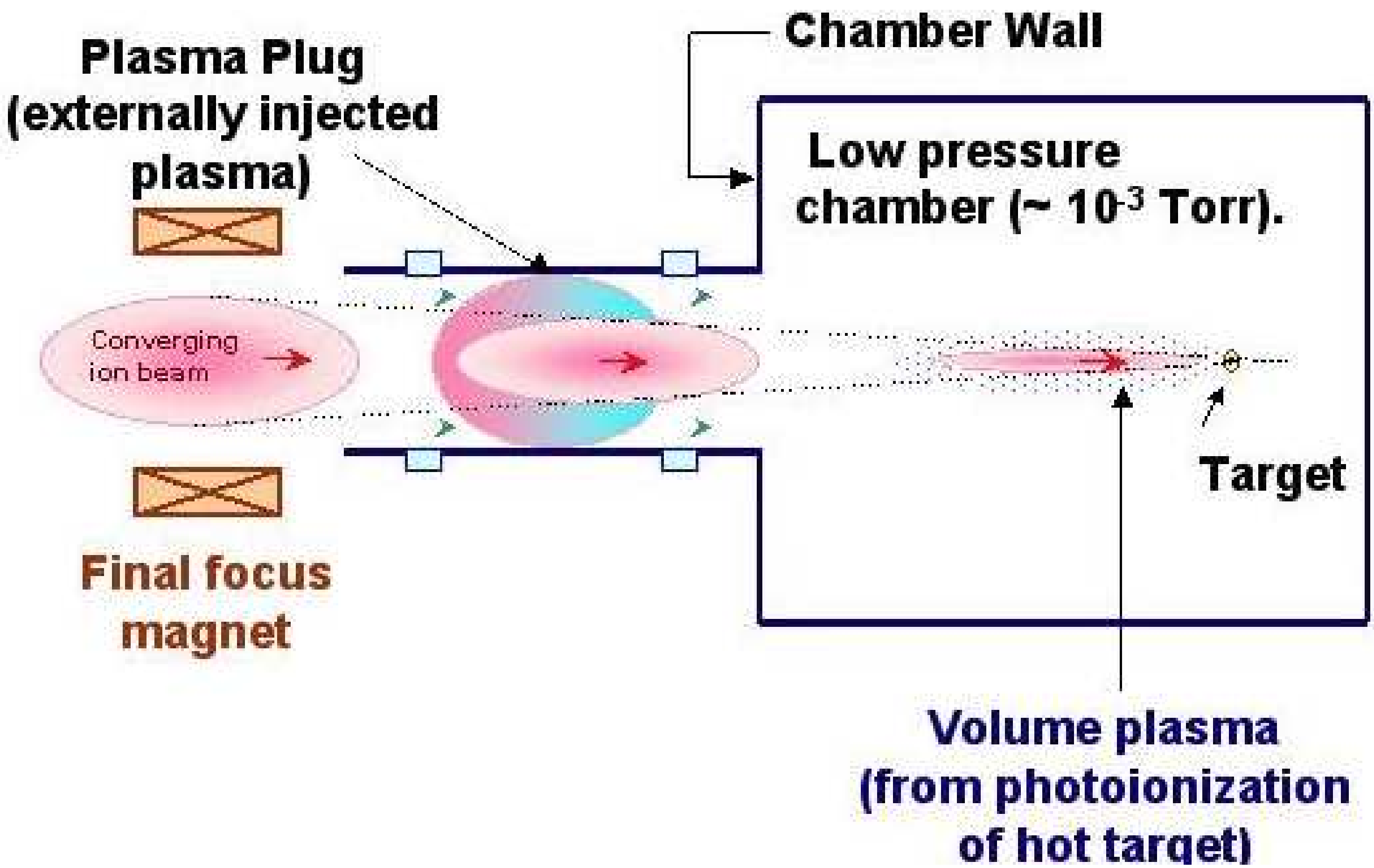
It can be "gated" in time

Isosurface upon which $f(x,y,x') = 0.3\ f_{max}$

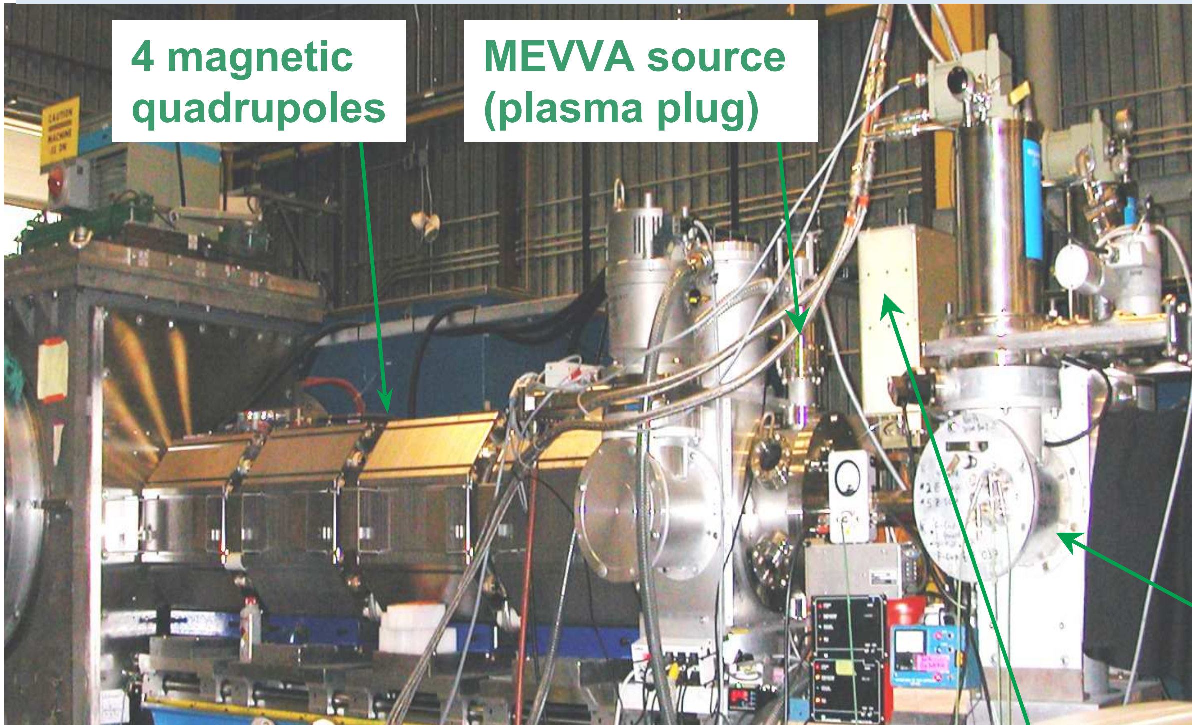


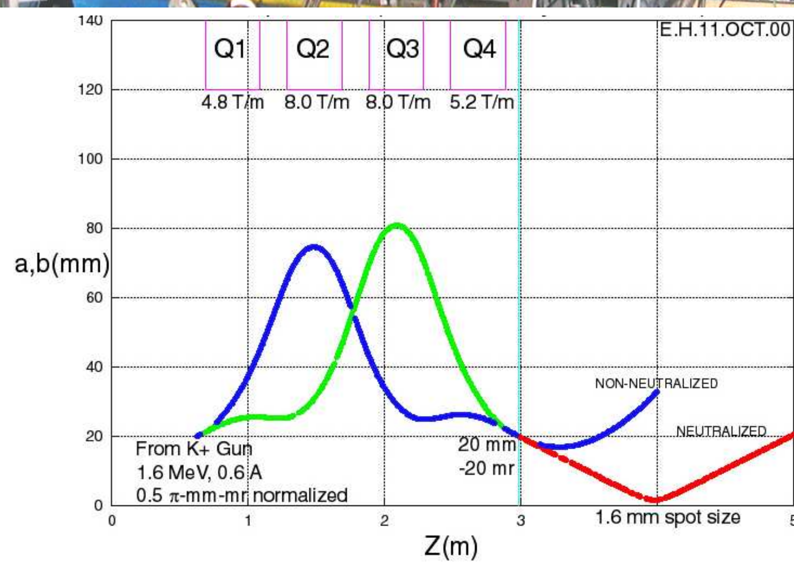
NTX

Neutralization competes with stripping in the target chamber

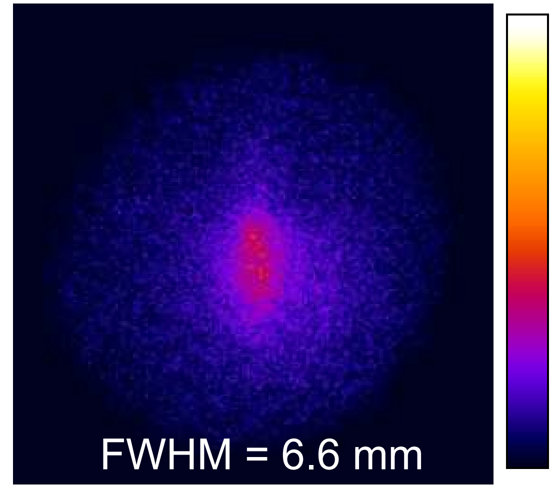


The Neutralized Transport Experiment (NTX) enables studies of beam neutralization and focusing

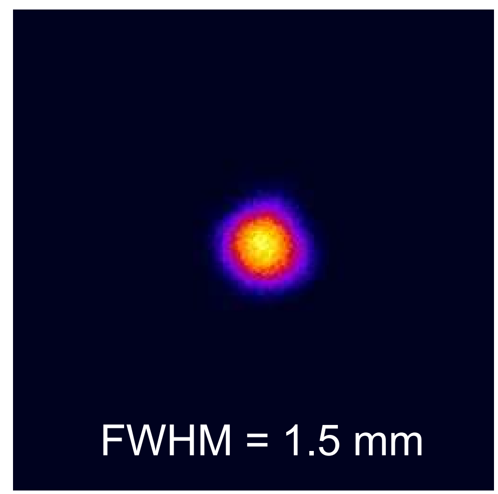




Non-neutralized



Plasma plug + volume plasma



Variation of beam image vs. quadrupole strength shows good agreement of NTX data with WARPxy simulations

Images at entrance to neutralized transport section

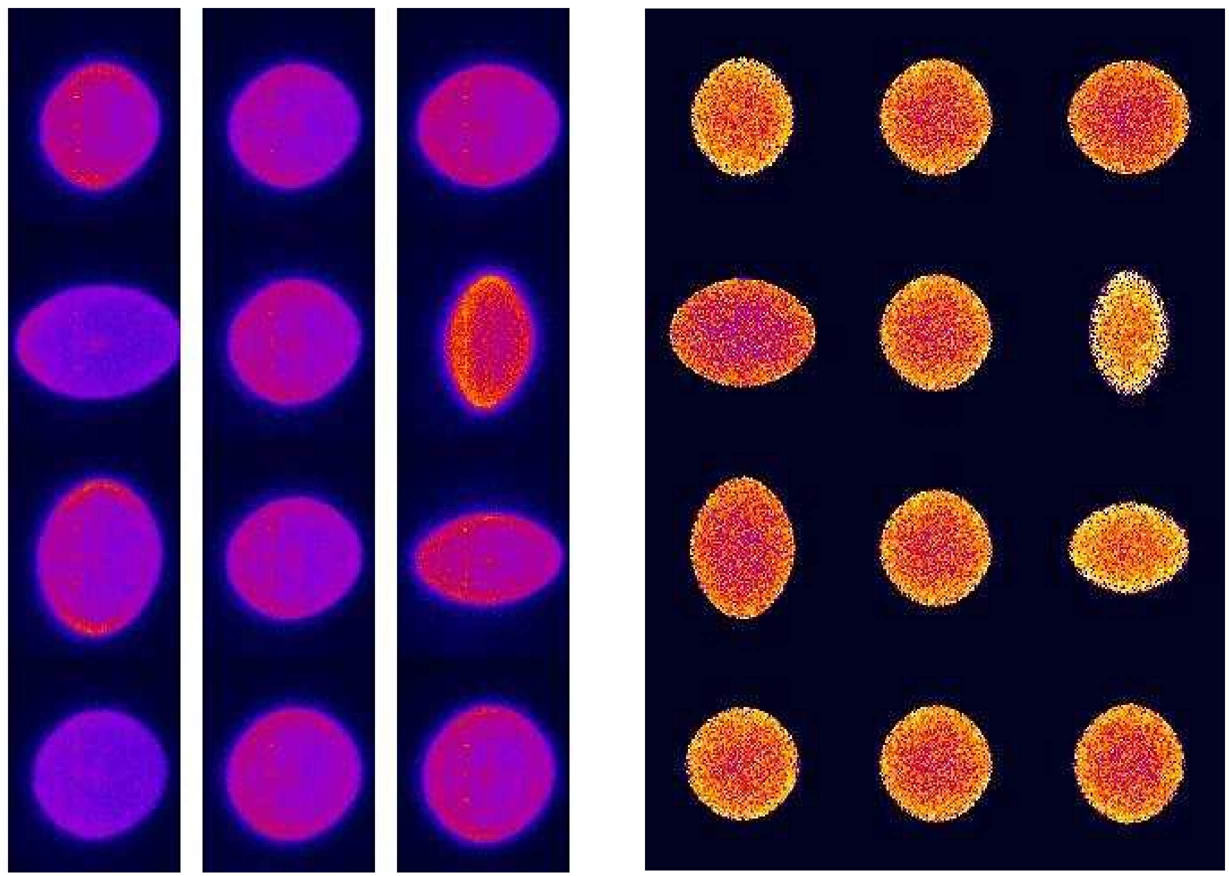
Experiment Simulation

ΔQ1= ± 5%

ΔQ2= ± 2%

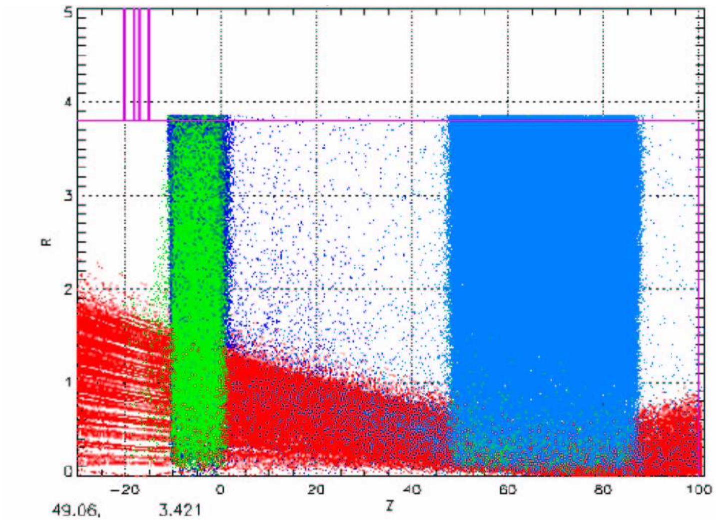
ΔQ3= ± 2%

ΔQ4= ± 2%

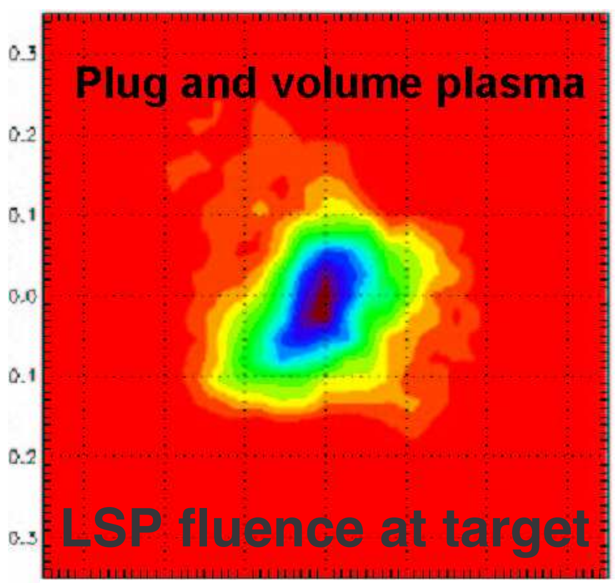


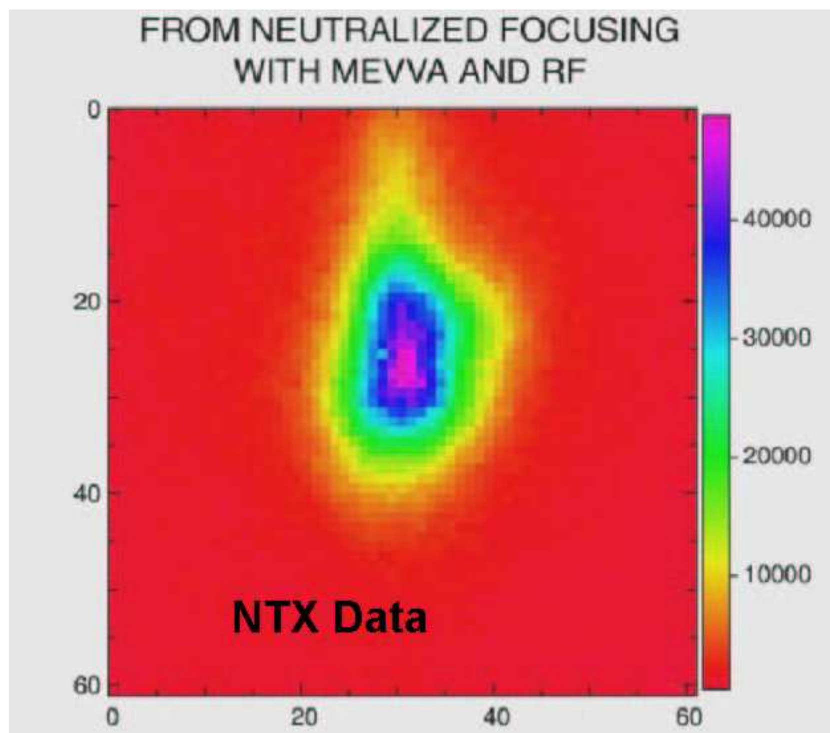
Nominal energy and fields

LSP simulations of NTX transport are now being initialized with the measured 4D particle distribution



- EM, 3D cylindrical geom., 8 azimuthal spokes
- 3 eV plug 3×10^{9} cm^{-3}, volume plasma 10^{10} cm^{-3}



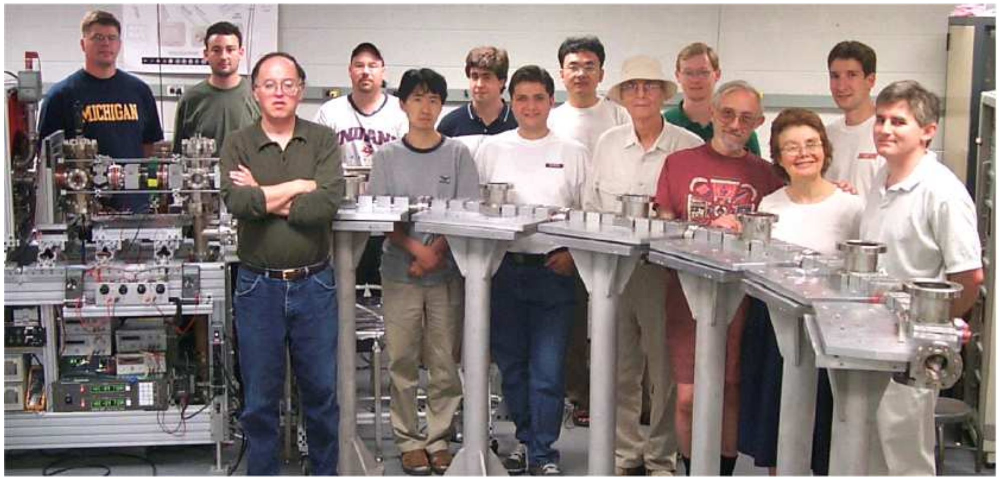


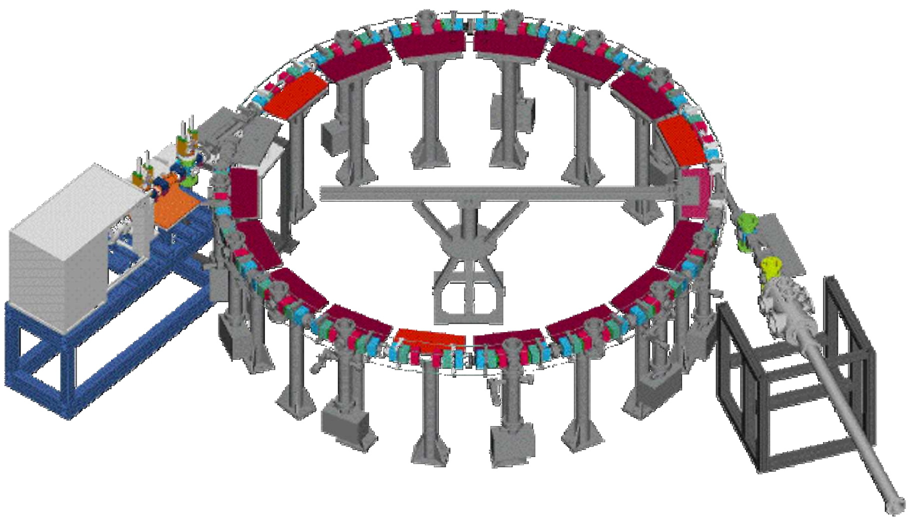
Carsten Thoma, et. al.

scaled exp'ts

Small-scale experiments are studying long-path transport physics

Univ. of Maryland Electron Ring (UMER)



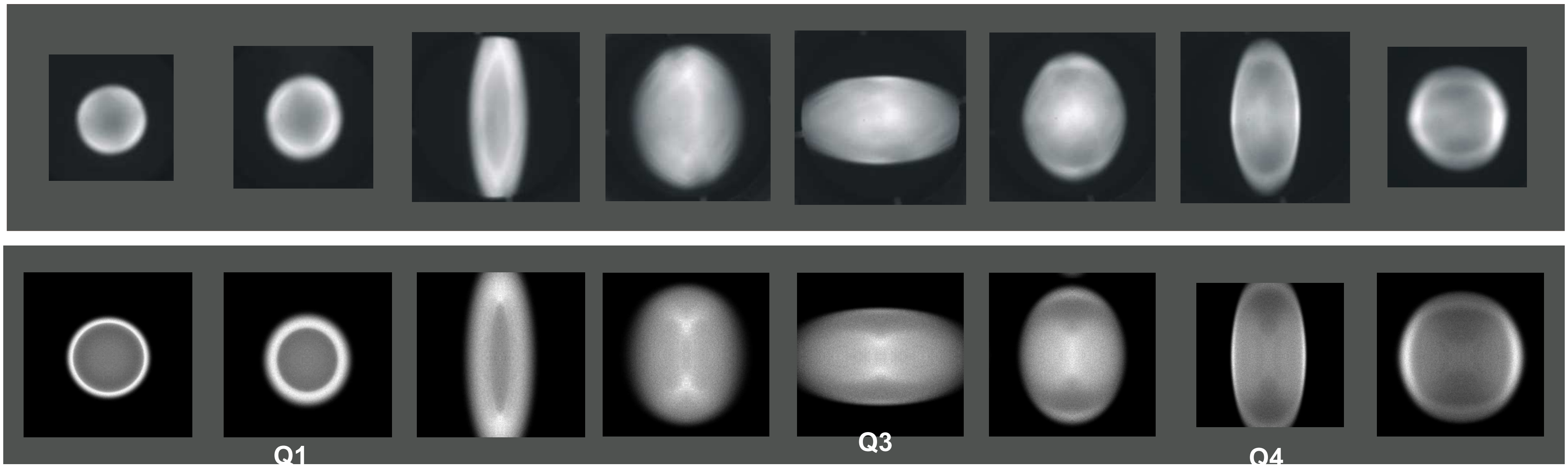


Princeton's Paul Trap Simulator Experiment

Ion bunch confined in oscillating electric quadrupole field; equivalent to 1000's of lattice periods

Scaled electron ring at U. MD is simulated using WARP

Experiment (top) vs. WARP simulation (bottom)



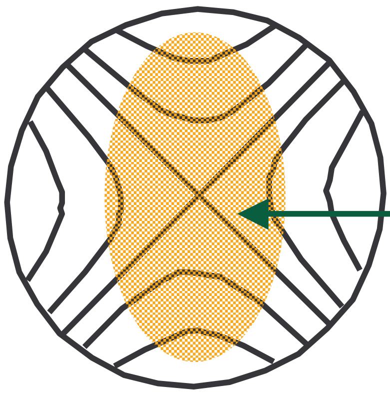
The rings are due to edge lensing

III. Fundamental beam science studies center on "afflictions and avoidance thereof"

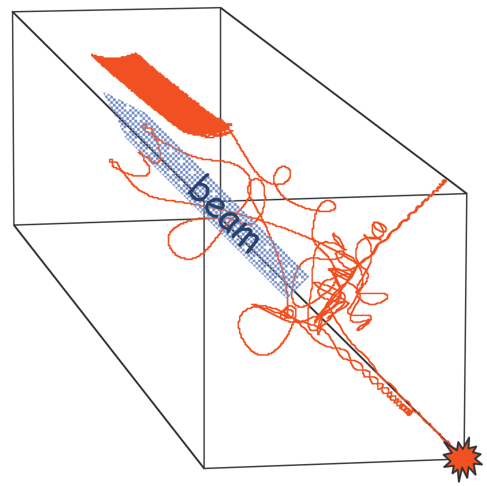
- Electron cloud
- Instabilities
- Beam halo

e - cloud

Experiments and simulations explore sources, sinks, and dynamics of stray electrons



Electrons can trap into beam space-charge and quadrupole magnetic fields



Electron lifetime ~ time to drift out the end of a magnetic quadrupole

Stray electron density derives from beam ionization of gas + ion flux to wall $\times$ e^-'s per incident ion $\times$ e^- lifetime

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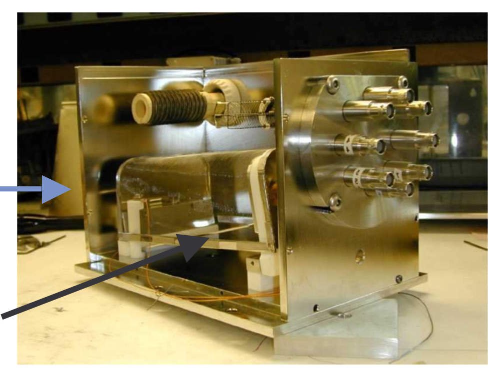
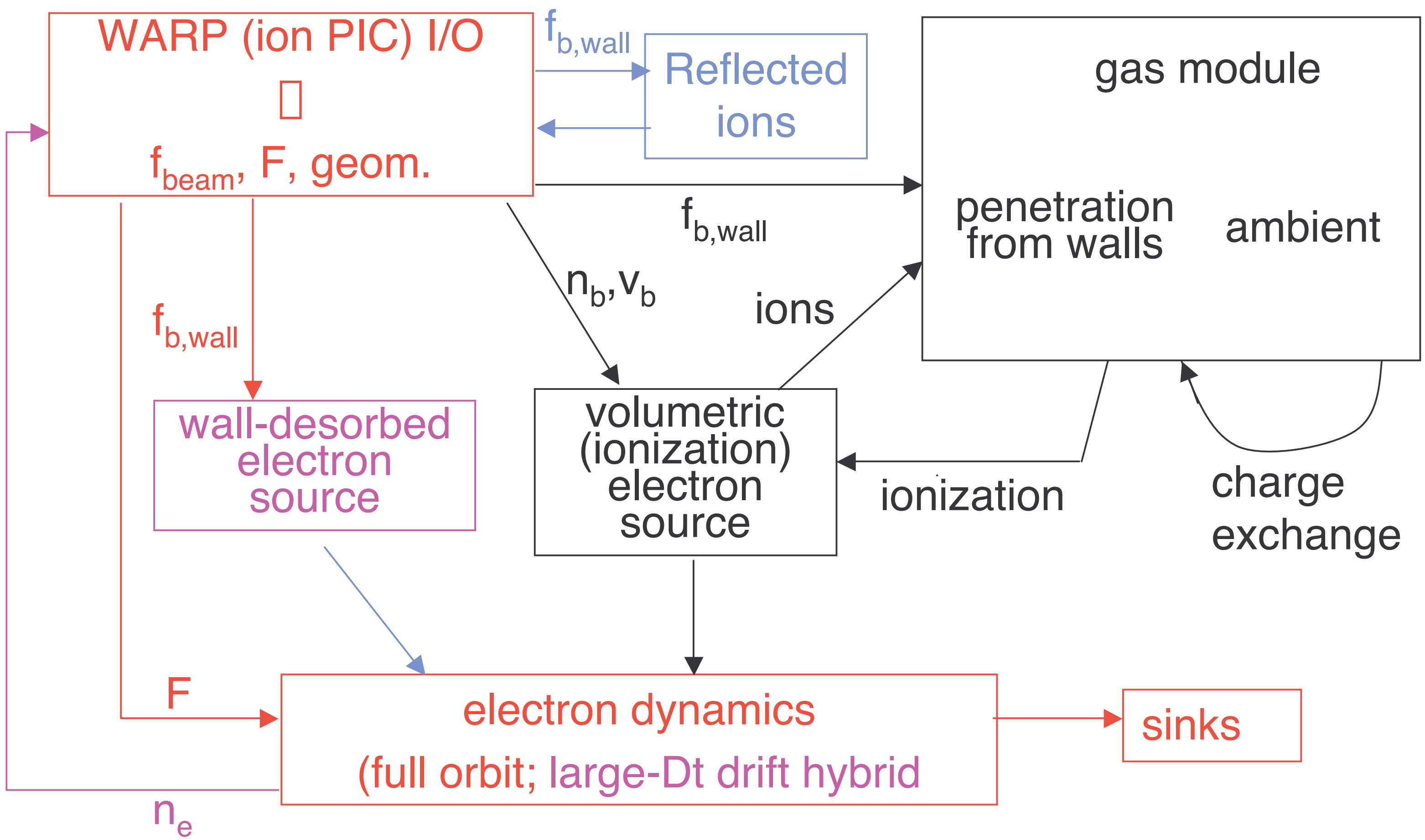
Gas, electron source diagnostic ⇒ for number and energy of electrons and gas molecules produced per incident ion

Beam

Tiltable target



We are following a road map toward toward self-consistent e-cloud and gas modeling in WARP

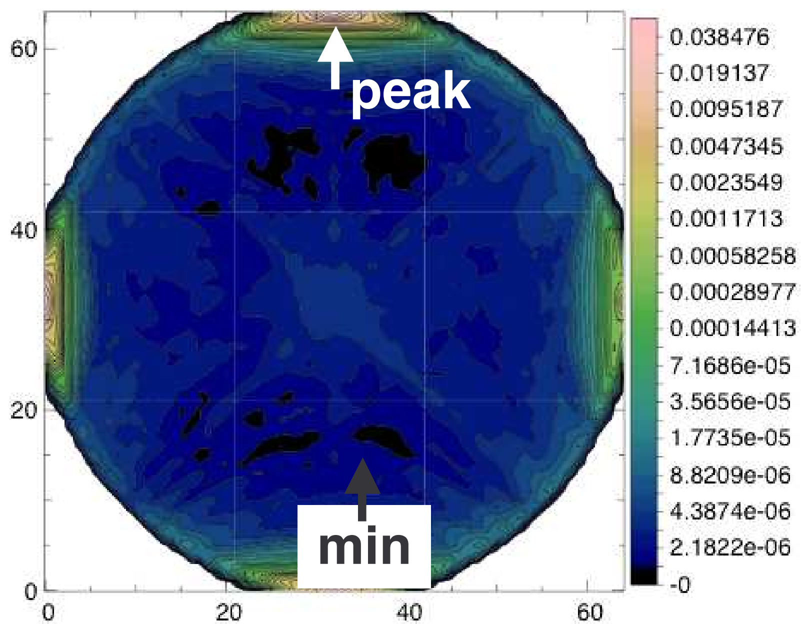


operational; implemented / testing; partially implemented; offline development

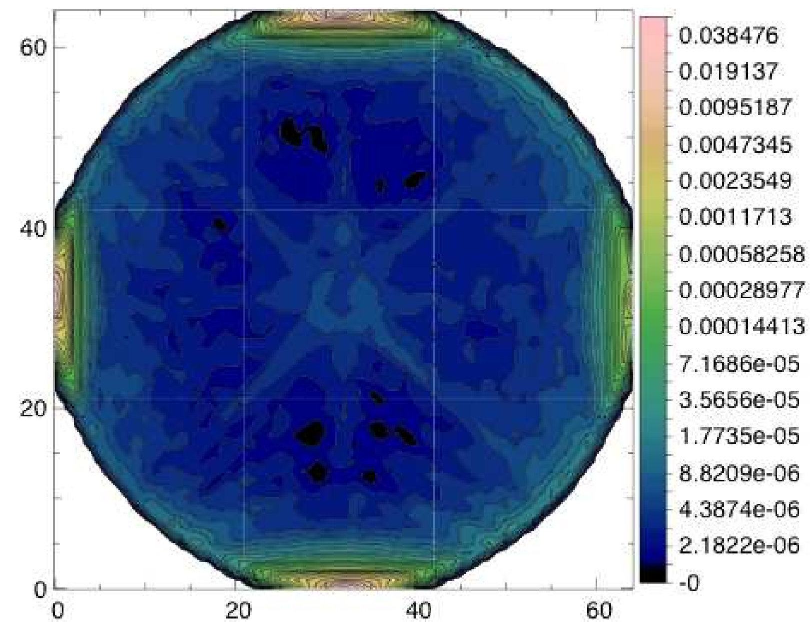
New large time-step electron mover reduces computational effort by factor of 25

Simulated wall-desorbed electron density distributions (log scale)

Full-orbit , $\Delta t=.25/f_{ce}$



Large time-step interpolated

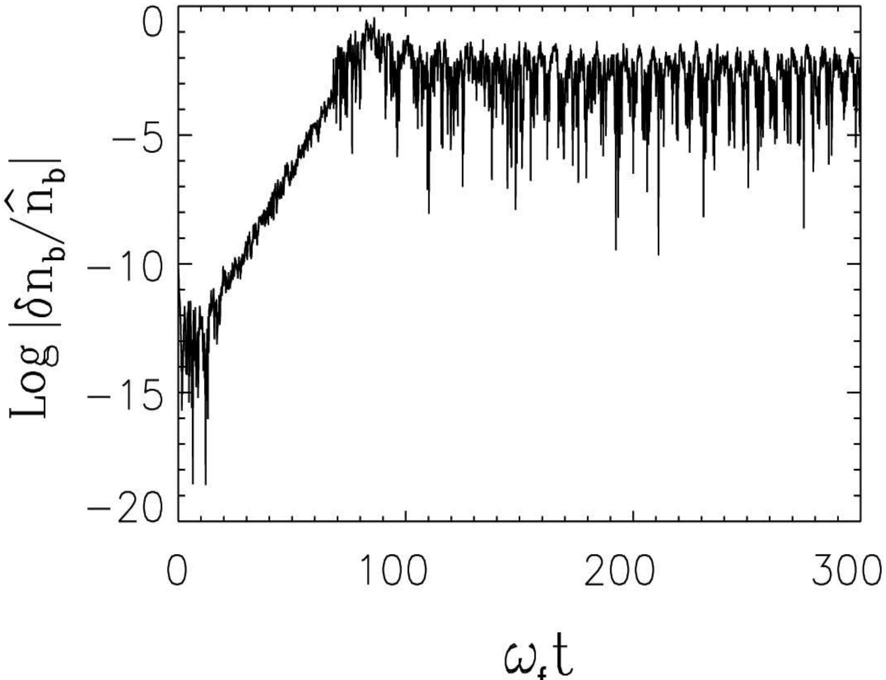


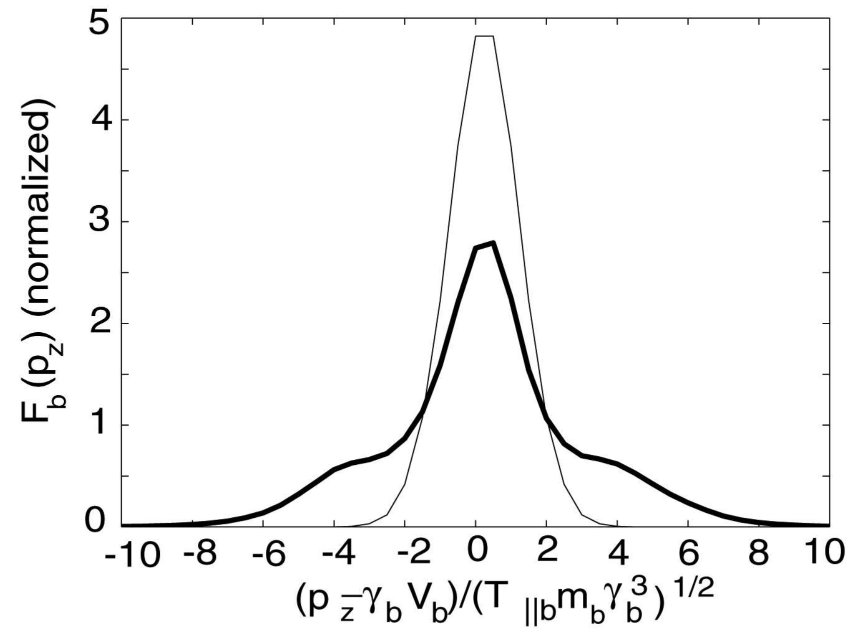
Electrons in 45° regions caused by first-flight reflected ions

We envision possible applications in MFE, astrophysics, near-space, …
See Ron Cohen's invited talk at APS-DPP 2004

Instabilities

Nonlinear δf simulations reveal properties of electrostatic anisotropy-driven mode

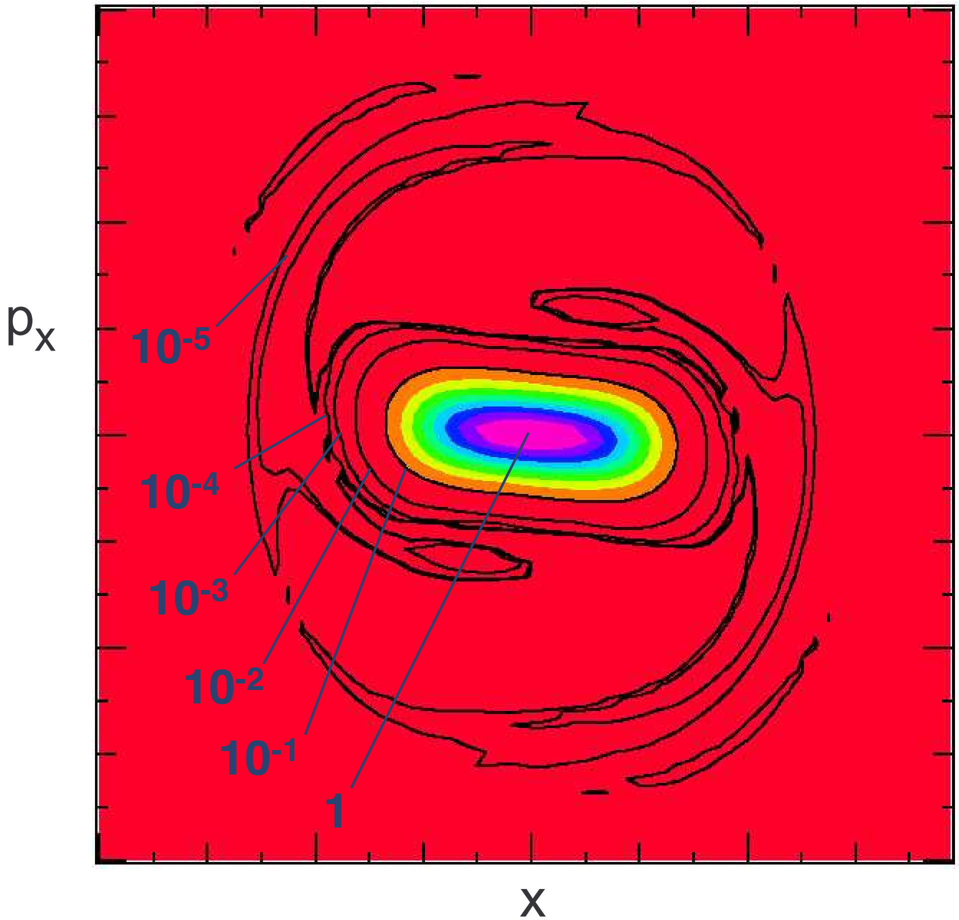




- When $T_\perp > T_\|$, free energy is available for a Harris-like instability
- Earlier work (1990 …) used WARP
- Simulations using BEST δf model (above) show that the mode saturates quasilinearly before equipartitioning; final $\Delta v_\| \approx \Delta v_\perp / 3$
- BEST was also applied to Weibel; that mode appears unimportant for energy isotropization
- BEST, LSP, and soon WARP are being applied to 2-stream

Halo

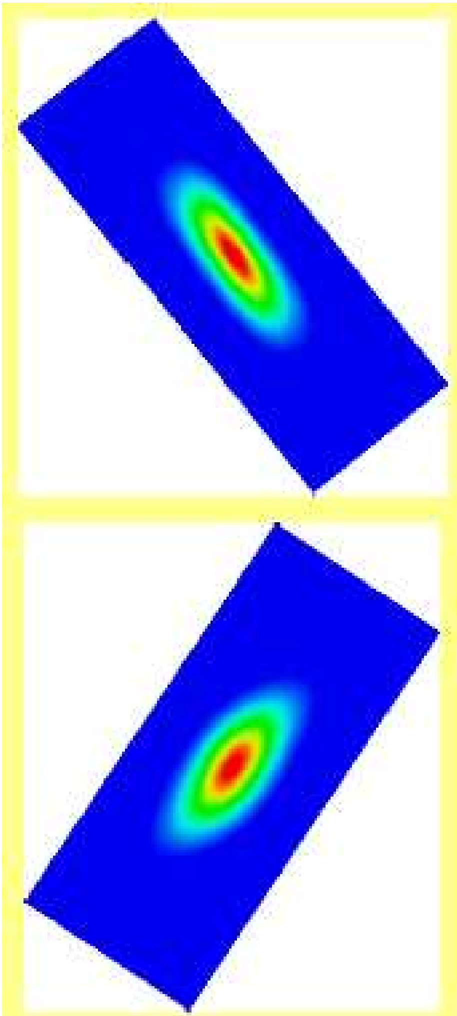
Solution of Vlasov equation on a grid in phase space offers low noise, large dynamic range



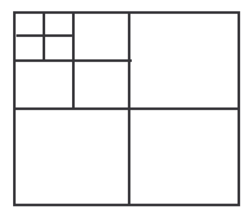
Evolved state of density-mismatched axisymmetric thermal beam with tune depression 0.5, showing halo

- 4D Vlasov testbed (with constant focusing) showed halo structure down to extremely low densities

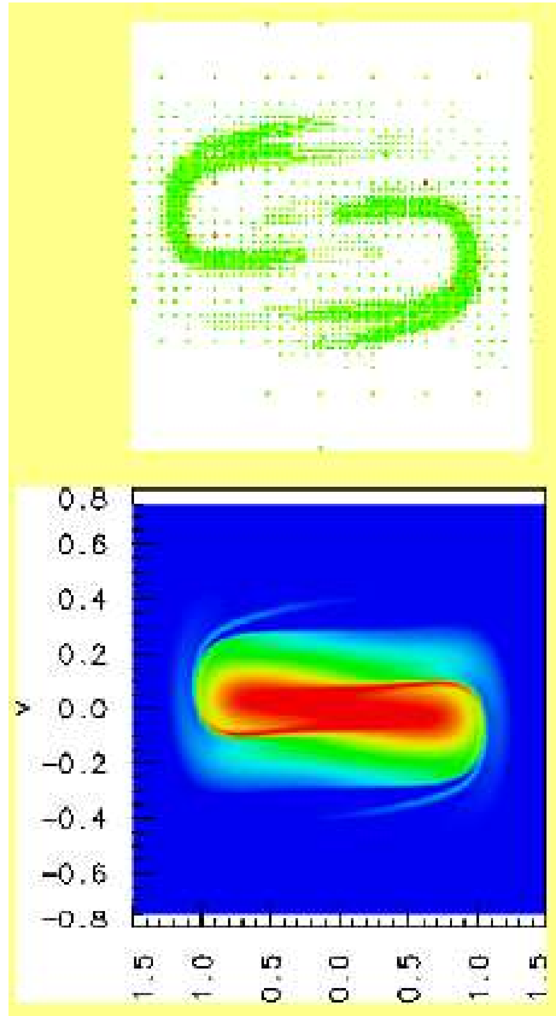
New ideas include moving grid in phase space to model quadrupoles, adaptive mesh to resolve fine structures



moving phase-space grid, based on non-split semi-Lagrangian advance



adaptive mesh in phase space



IV. Simulations enable exploration of future experiments

- Neutralized Drift Compression Experiments (NDCX sequence) & Modular Driver (MD)
- Integrated Beam Experiment (IBX) & Robust Point Design (RPD)

NDCX & MD

HIF requires High Energy Density Physics (HEDP); strongly-coupled 1-eV plasmas will come first

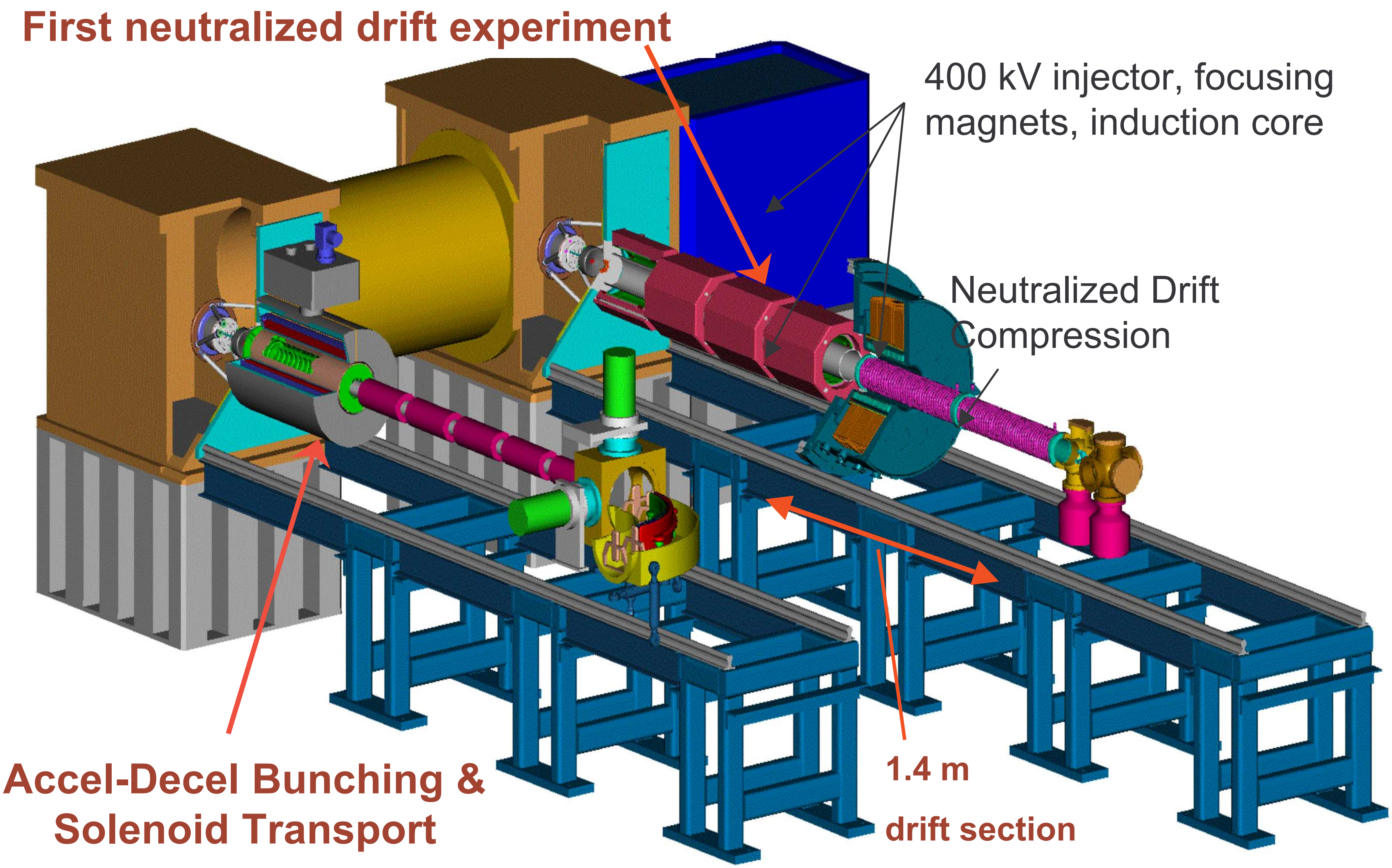
- HEDP regime is $\gtrsim 10^{11}$ J/m^3 (NRC)
- Ex: an integrated beam physics expt (NDCX-2, ~FY09):

  He$^+$, 10 A, 2 MeV, r_{spot} = 1 mm

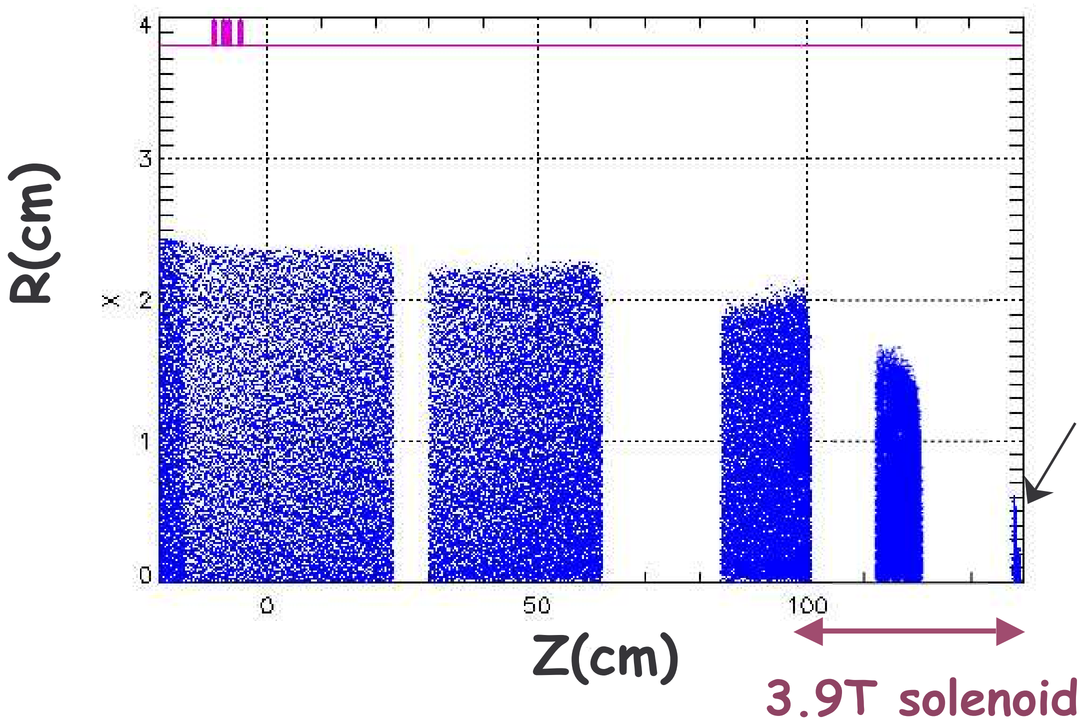
  $\tau_p \ll$ 1 ns (pulse duration $\ll$ hydrodynamic disassembly time)

- Must:
  - Produce the beam
  - Compress it longitudinally
  - Focus it
- Approach:
  - "Accel-decel" or other short-pulse injector
  - Neutralization to allow drift compression in short distance
  - Final focusing system with large chromatic acceptance

NDCX-1 experiments (FY06-07) will study neutralized compression by factors of 10-100



LSP simulations of neutralized drift and focusing show possibility of strong compression in NDCX-1



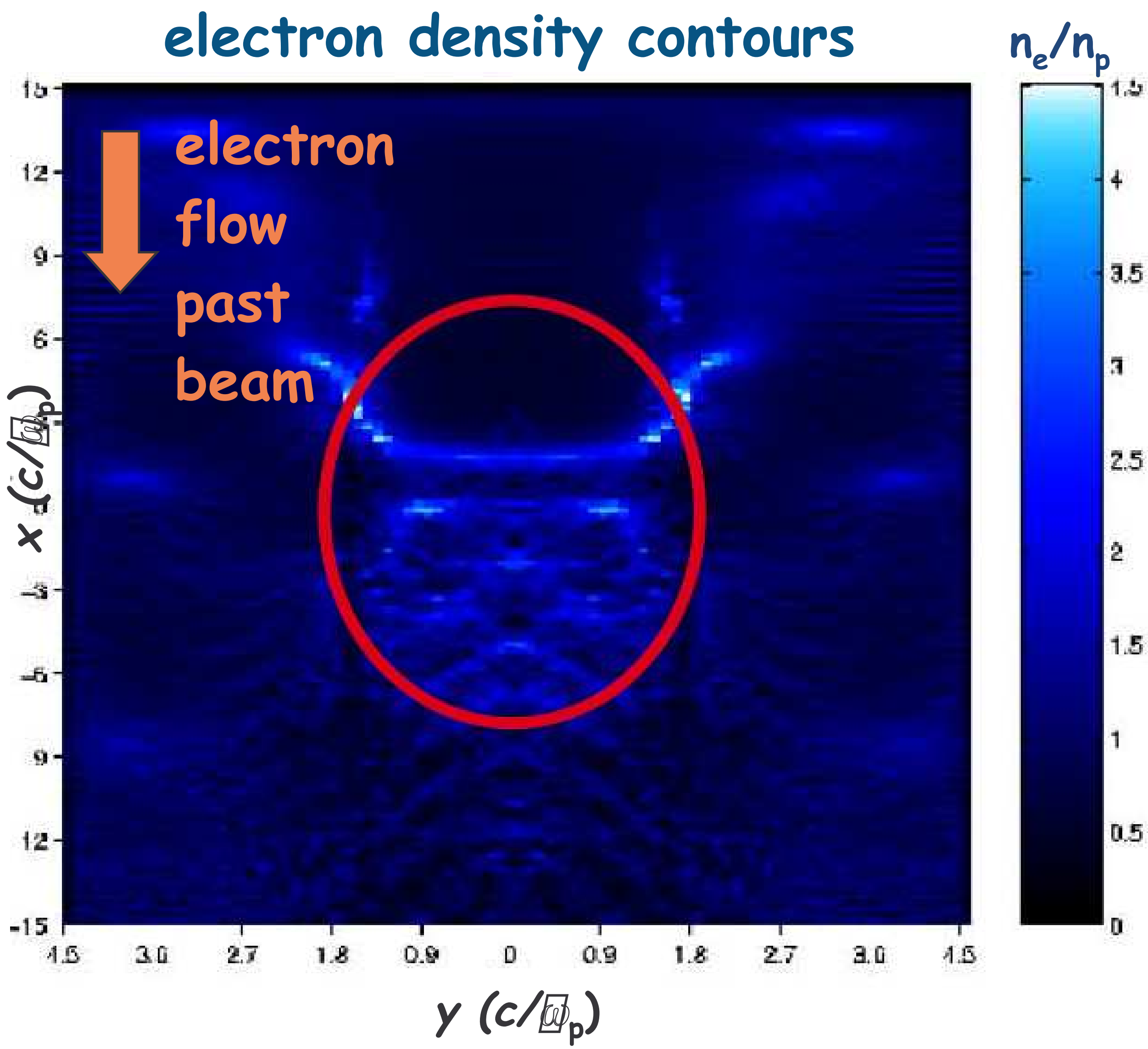
As simulated:

- *Axial compression* 120 X
- Radial compression to 1/e focal spot radius < 1 mm
- *Beam intensity on target increases by 50,000 X.*

Ramped 220-390 keV, K^+, 24 mA ion beam injected into a 1.4-m long plasma column with density 10 x beam density.

(simulations by Welch, Rose, Henestroza, Yu)

Simulation of ion pulse neutralization: waves induced in plasma are modified by a uniform axial magnetic field

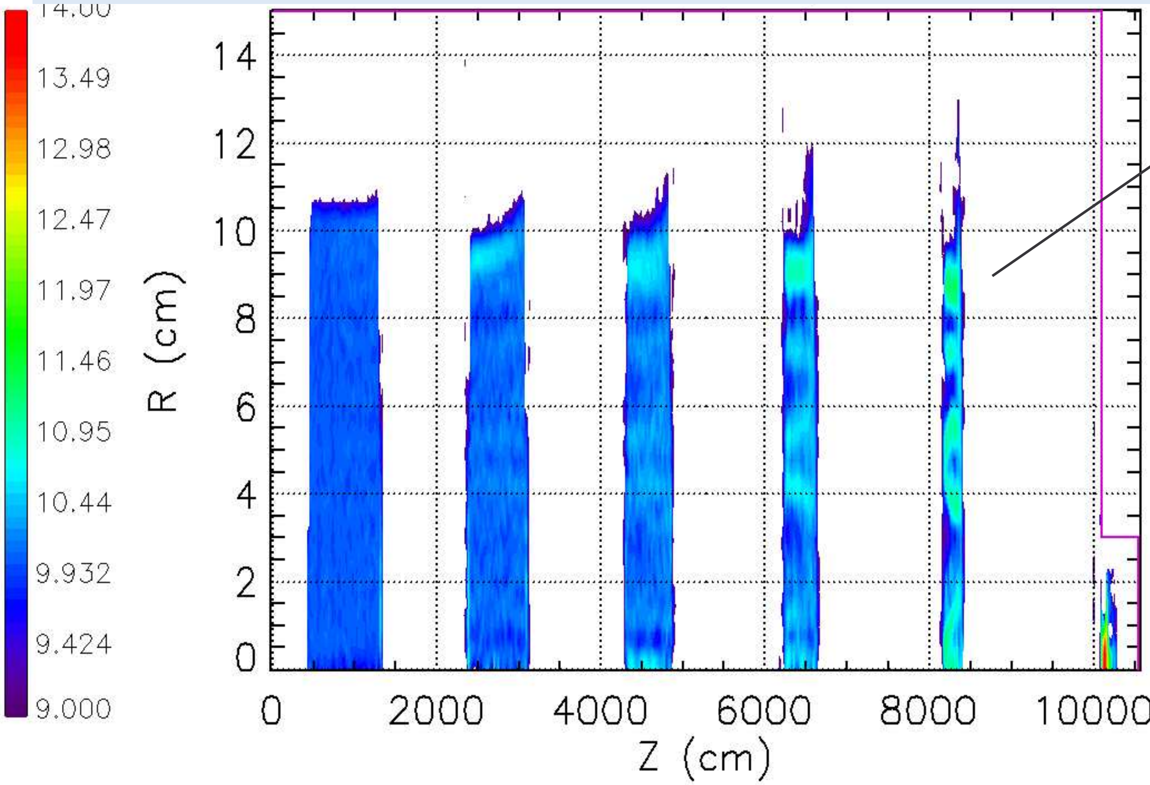


2D EM PIC code "EDPIC" in XY slab geometry, comoving frame, beam & plasma ions fixed

Analytic theory & simulation by Igor Kaganovich

$v_b = c/2$; $l_b = 7.5\ c/\omega_p$;
$\omega_c = 5\omega_p$; $r_b = 1.5\ c/\omega_p$;
$n_b = n_p/2$

LSP hybrid simulations of a "modular driver" show effectiveness of neutralized compression and focus



Run shows filamentation, but 92% of beam still falls within the 5 mm spot needed for a hybrid distributed radiator target

100-m plasma column

Ne+ beam
Pulse energy: 140 kJ
Energy ramp: 200 - 240 MeV
Current: 3→ 140 kA
Beam radius: 10 cm → < 5 mm
Pulse duration: 210→ 5 ns

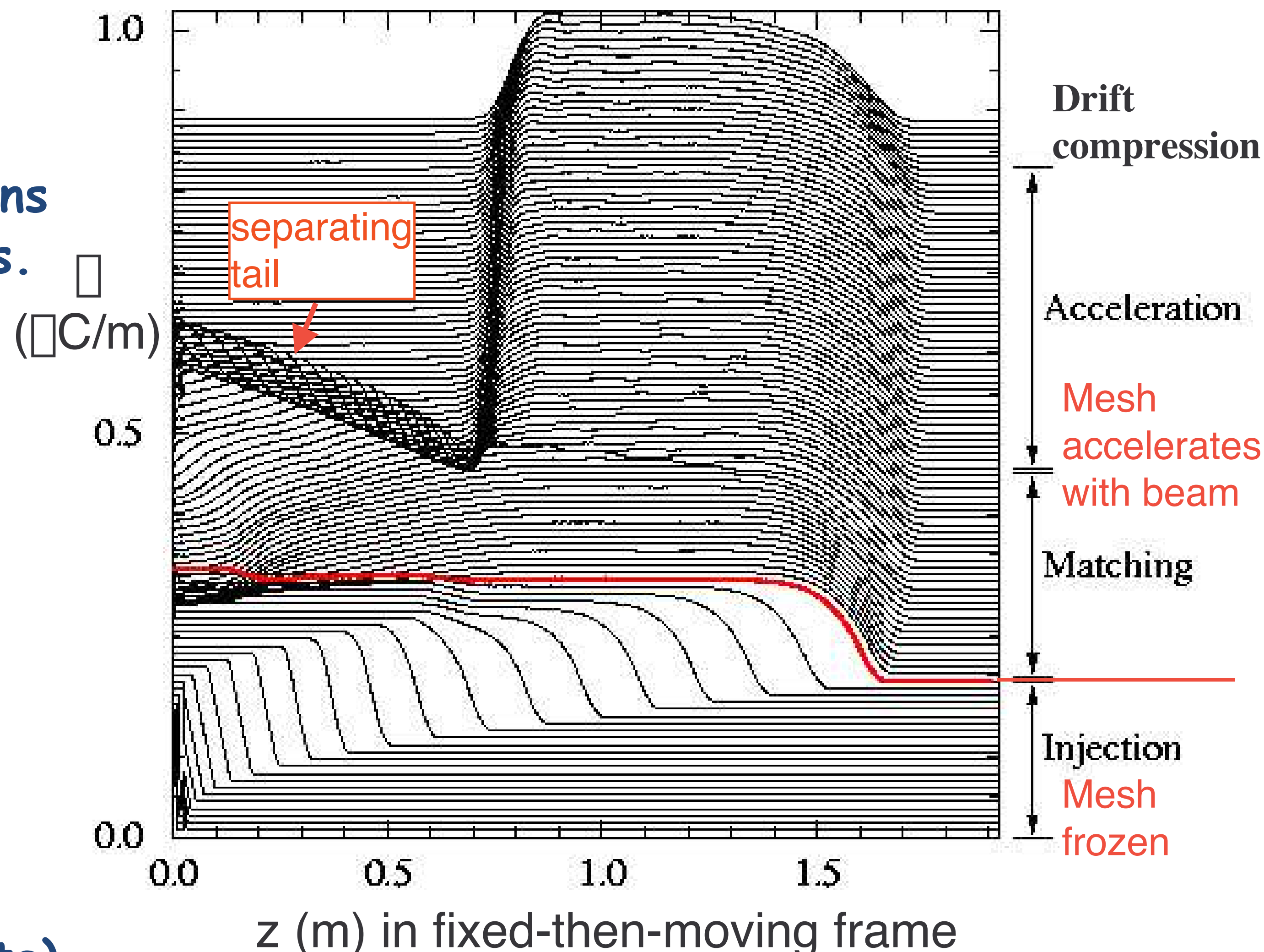
(Simulations by D.Welch & D. Rose)

3D WARP simulations of an "ideal" IBX show quiescent behavior

- Beam created at source, matched, accelerated, begins to drift-compress.

- Parameters:
  - 1.7 → 6.0 MeV
  - 200 → 100 ns
  - 0.36 → 0.68 A
  - 4.6 µs of beamtime

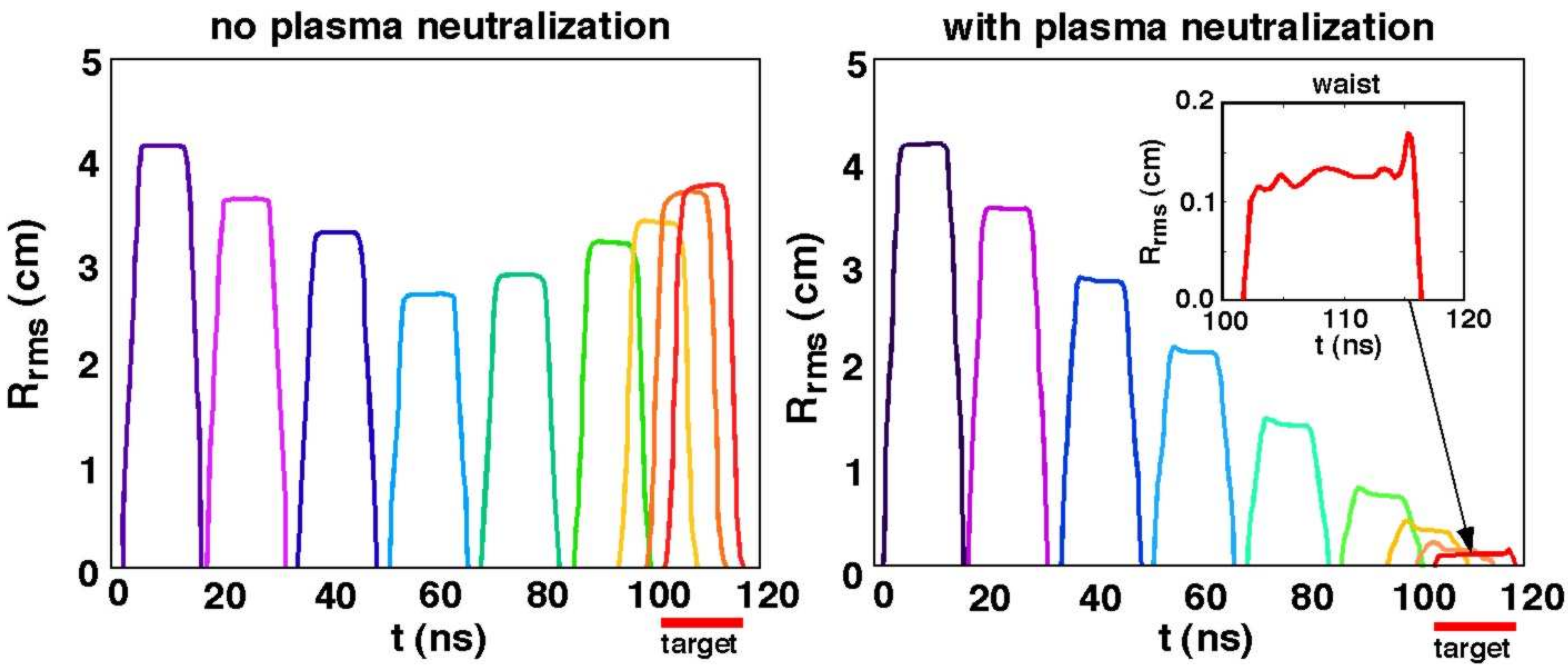
Line-charge at 100 successive times (vertically offset)



(D. P. Grote)

Neutralization of an "RPD" main pulse in fusion chamber yields a focal spot with 1.2 mm RMS radius

Beam radius vs. time at selected points over a 6-m focal length:



2 kA, 4 GeV, Bi^+

(LSP simulations by W. Sharp)

Discussion

Program needs drive us toward "multiscale, multispecies, multiphysics" modeling

- **e-Cloud and Gas:**
  - merging capabilities of WARP and POSINST; adding new models
  - implementing method for bridging disparate e & i timescales

- **Plasma interactions:**
  - LSP already implicit, hybrid, with collisions, ionization, … now with improved one-pass implicit EM solver
  - Darwin model development (W. Lee et. al.; Sonnendrucker)

- **Injectors**
  - Merging beamlet approach is multiscale
  - Plasma-based sources (FAR-Tech SBIR)

- **New HEDP mission changes path to IFE; models must evolve too**
  - Non-stagnating pulse compression
  - Plasmas early and often
  - Modular approach a natural complement

Closing thoughts …

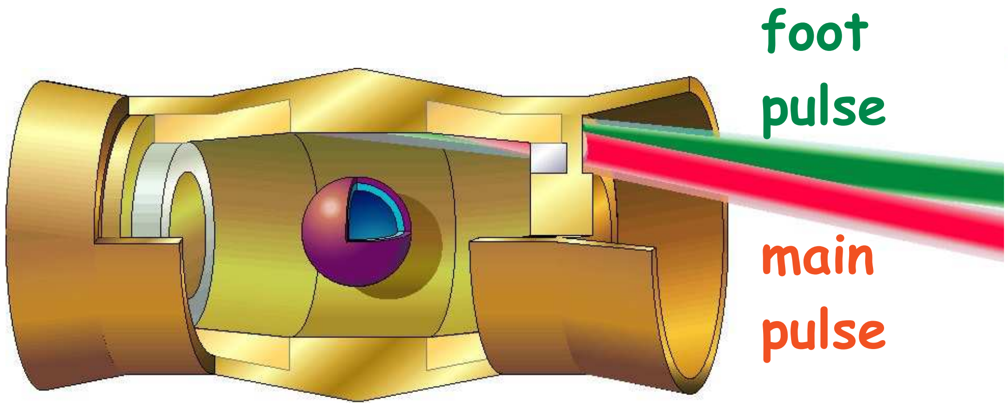
While simulations for Heavy Ion Fusion are at the forefront in terms of the relative strength of the space charge forces, a wide range of beam applications are pushing for higher intensity, and will benefit from this work

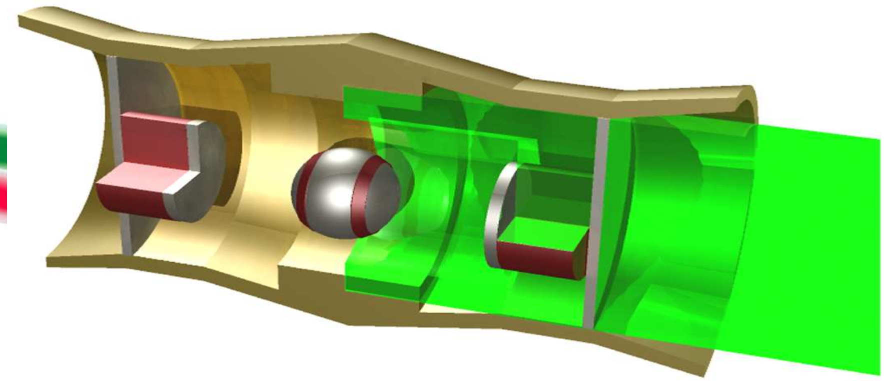
MFE applications may also benefit from AMR-PIC, Vlasov, e-mover, …

This talk drew on material from quite a few people - my thanks to all!

End

Targets set ultimate physics regime of beams





"Distributed radiator" target
Beam spot 1.8 mm x 4.1 mm
5.9 MJ beam energy
Gain = 68

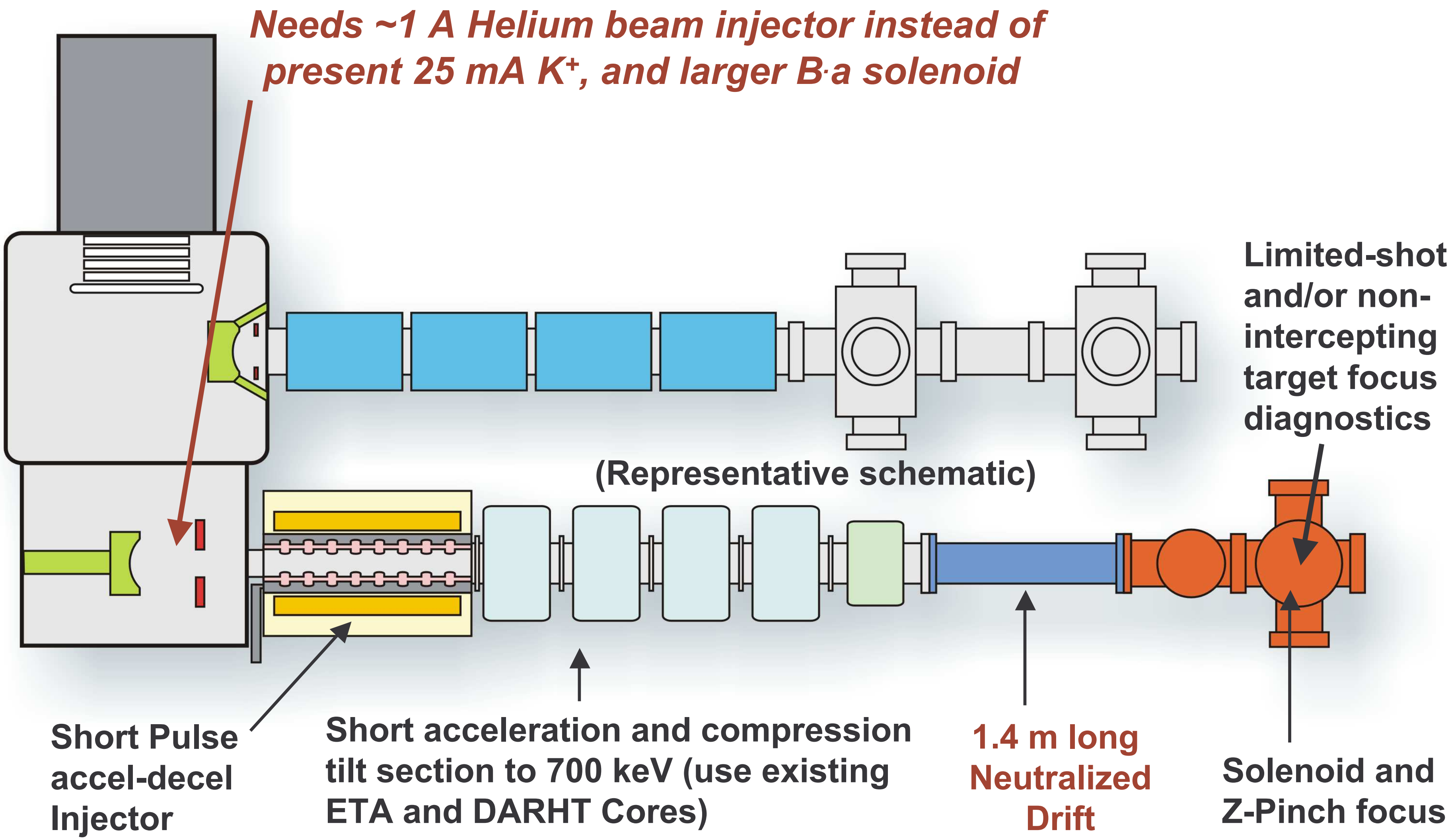
"Hybrid" target
Beam spot 3.8 mm x 5.4 mm
6.7 MJ beam energy
Gain = 58

E_{pulse} ~ 3-7 MJ; τ_{pulse} ~ 8-10 ns $\Rightarrow$ ~ 500 TW

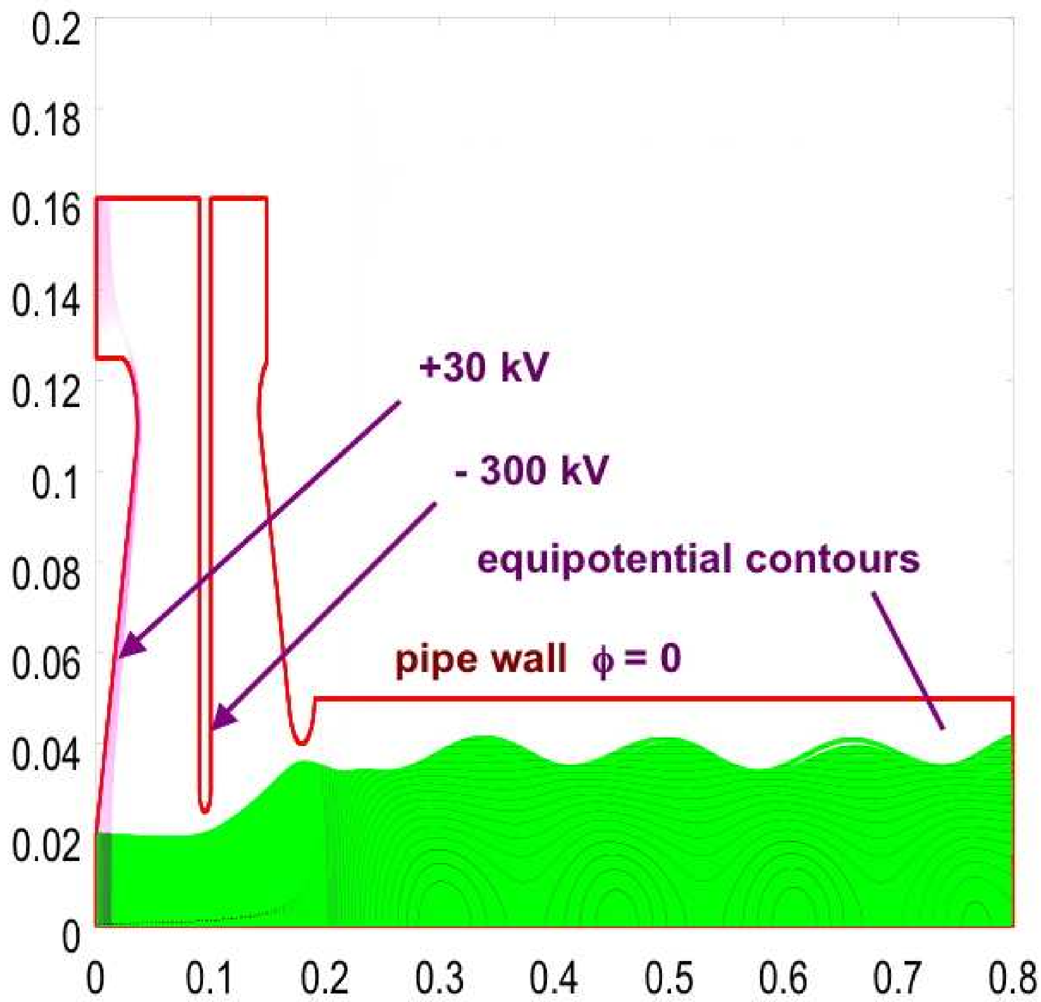
A ~ 100-200; range 0.02 - 0.20 g/cm^2 $\Rightarrow$ Ion energy 1 - 10 GeV

~10^{16} ions total, ~ 100 beams at ~ 2-4 kA/beam

FY09 Integrated beam experiments on neutralized compression and focusing to targets (NDCX-2)



Integrated beam simulation from source through injection into NDCX-2 decel /post acceleration section



r (m)

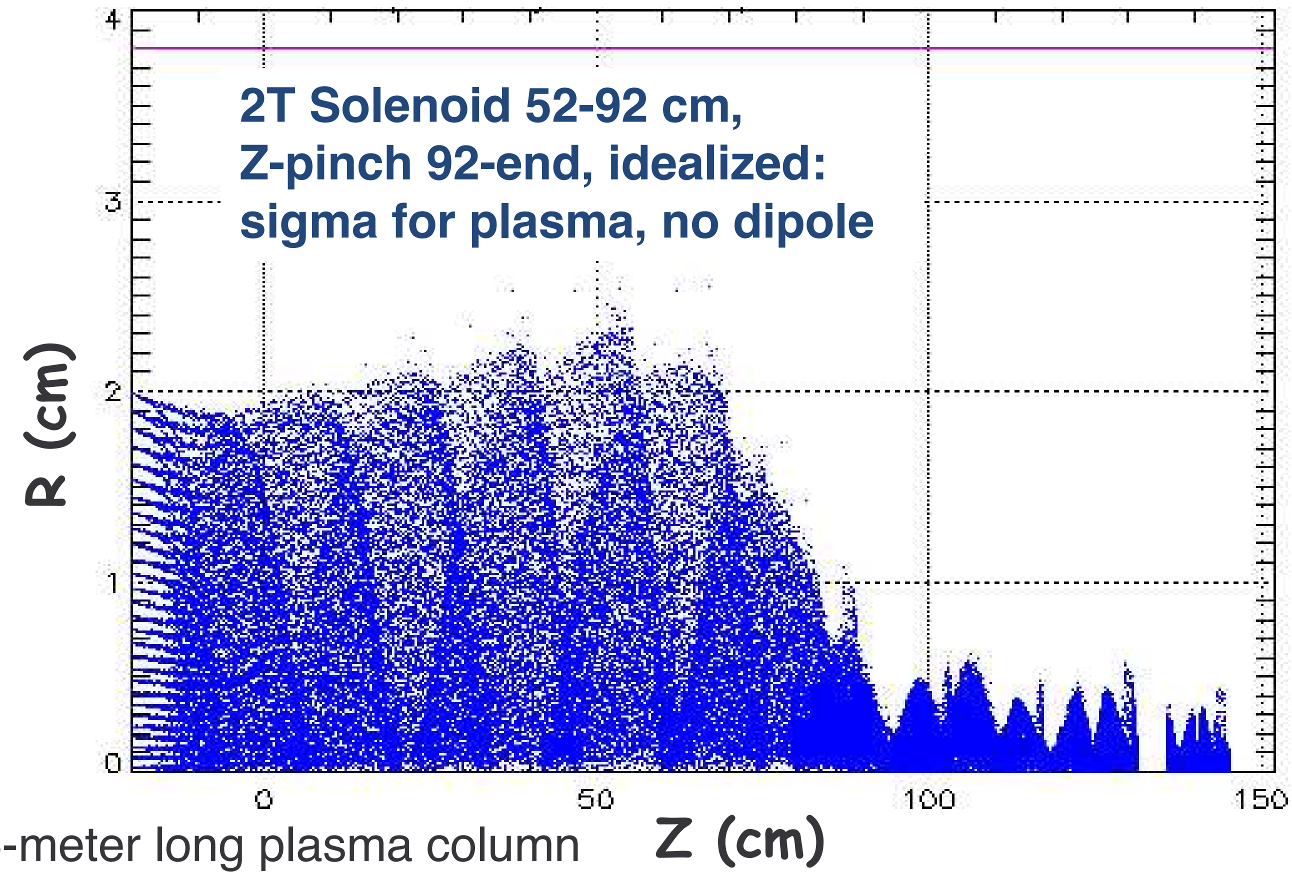
z (m)

This simulation of the NDCX-2 front end by Henestroza feeds into the simulation by Welch, *et. al.*, for the back end.

Beam bunches up to 1.2 μC/ m for post-acceleration

He^{+1} beam (1A at source)

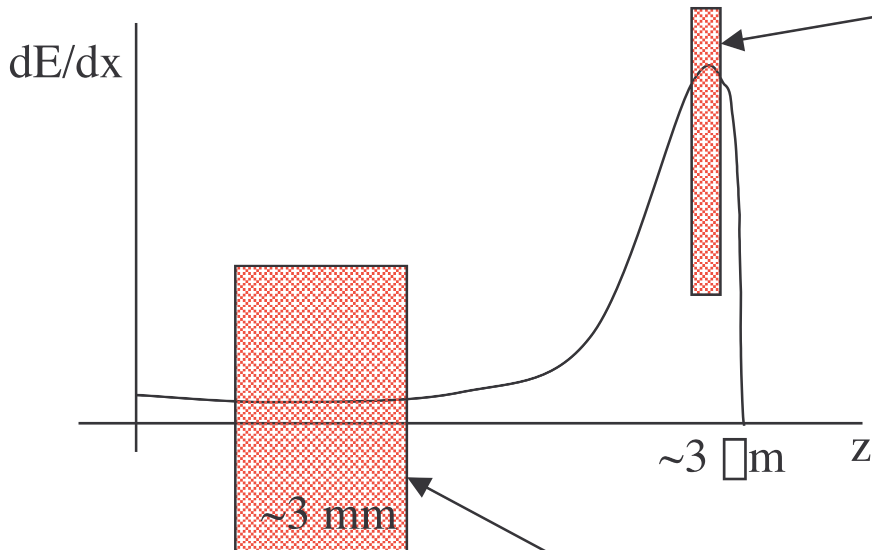
Preliminary LSP simulations show neutralized compression & focusing in NDCX-2, for 1st HIF exp'ts in HEDP regime



1.5-meter long plasma column
Beam: He+ ; Pulse energy: 0.7 J
Energy ramp: 500 - 1000 keV
Current: 10 → 750 A,
Pulse duration: 100 → 1 ns,
Beam radius: 20 → < 1 mm

(Simulations by D.Welch & D. Rose)

Two ion dE/dx regimes to obtain isochoric ion energy deposition in 1-to-few eV warm-dense matter targets



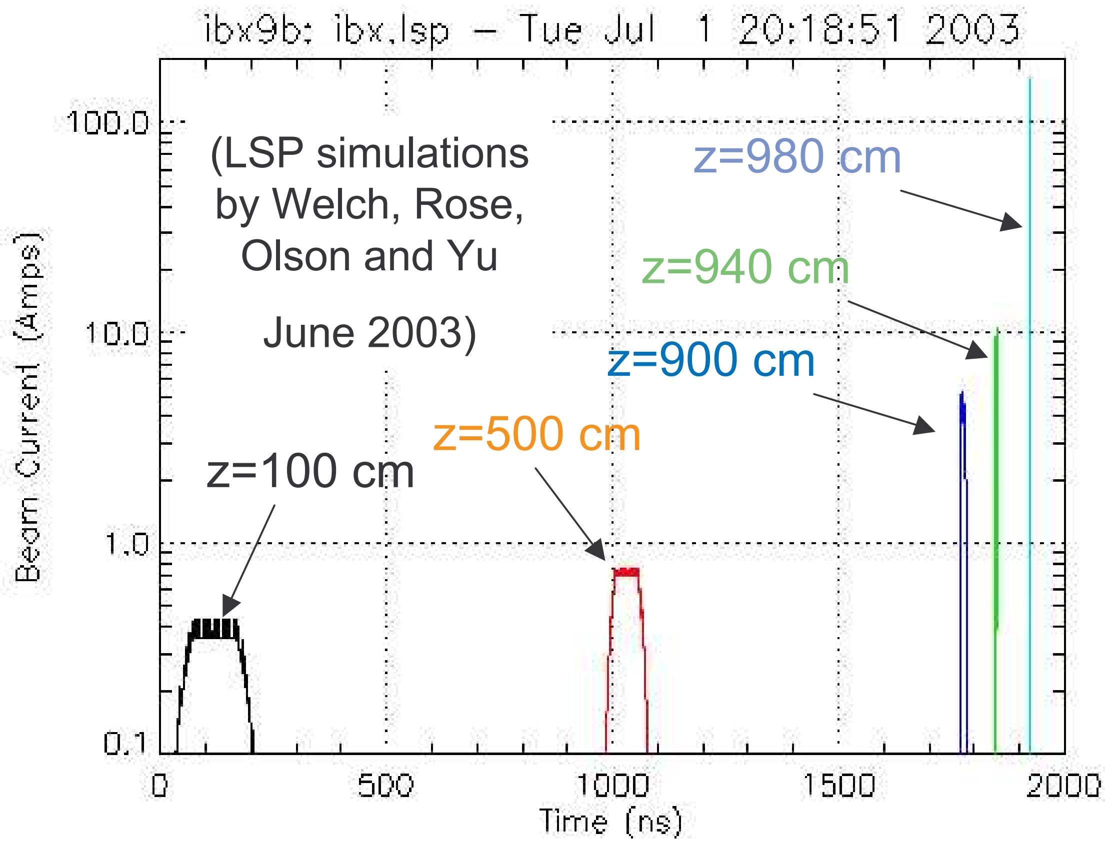
HIF linacs with ~ 0.5-1 J of ions @ ~0.3 MeV/u would work best heating thin foils near the Bragg peak where dE/dx~ 0

→ ~3 % uniformity possible (Grisham, PPPL). ***Key-issue: can < 300 ps ion pulses to avoid hydro-motion be produced?***

Heavy-ion beams of >300 MeV/u at GSI must heat thick targets with ions well above the Bragg peak→ kJ energies required @ <300 ns to achieve → ~15% uniformity.

Key issue for ion accelerator-driven HEDP: limits of beam compression, focusing and neutralization to achieve short (sub-ns) ion pulses with tailored velocity distributions.

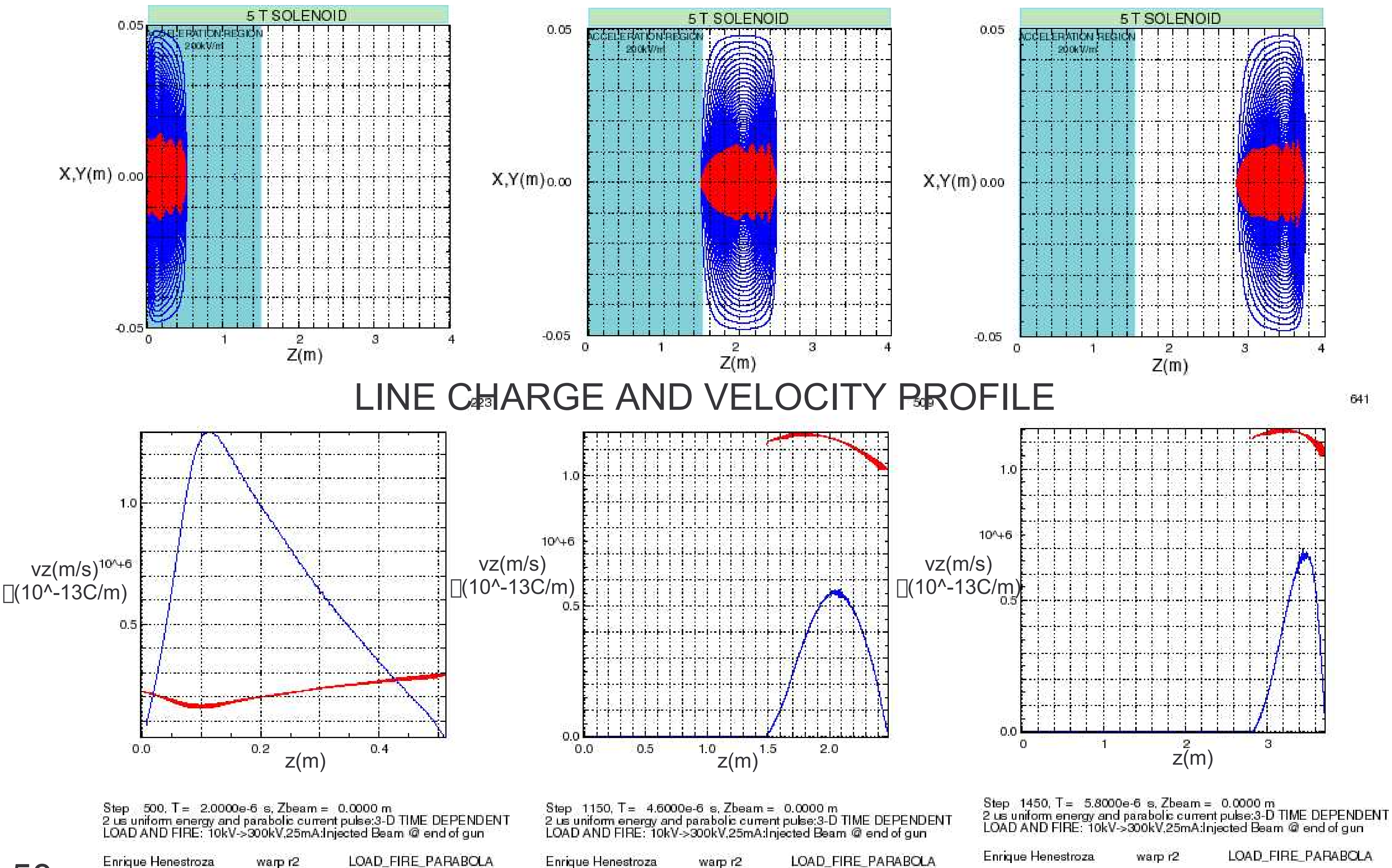
Recent HIF-VNL simulations of neutralized drift compression of heavy-ions in IBX are encouraging: a 200 ns initial ion pulse compresses to ~300 ps with little emittance growth and collective effects in plasma.



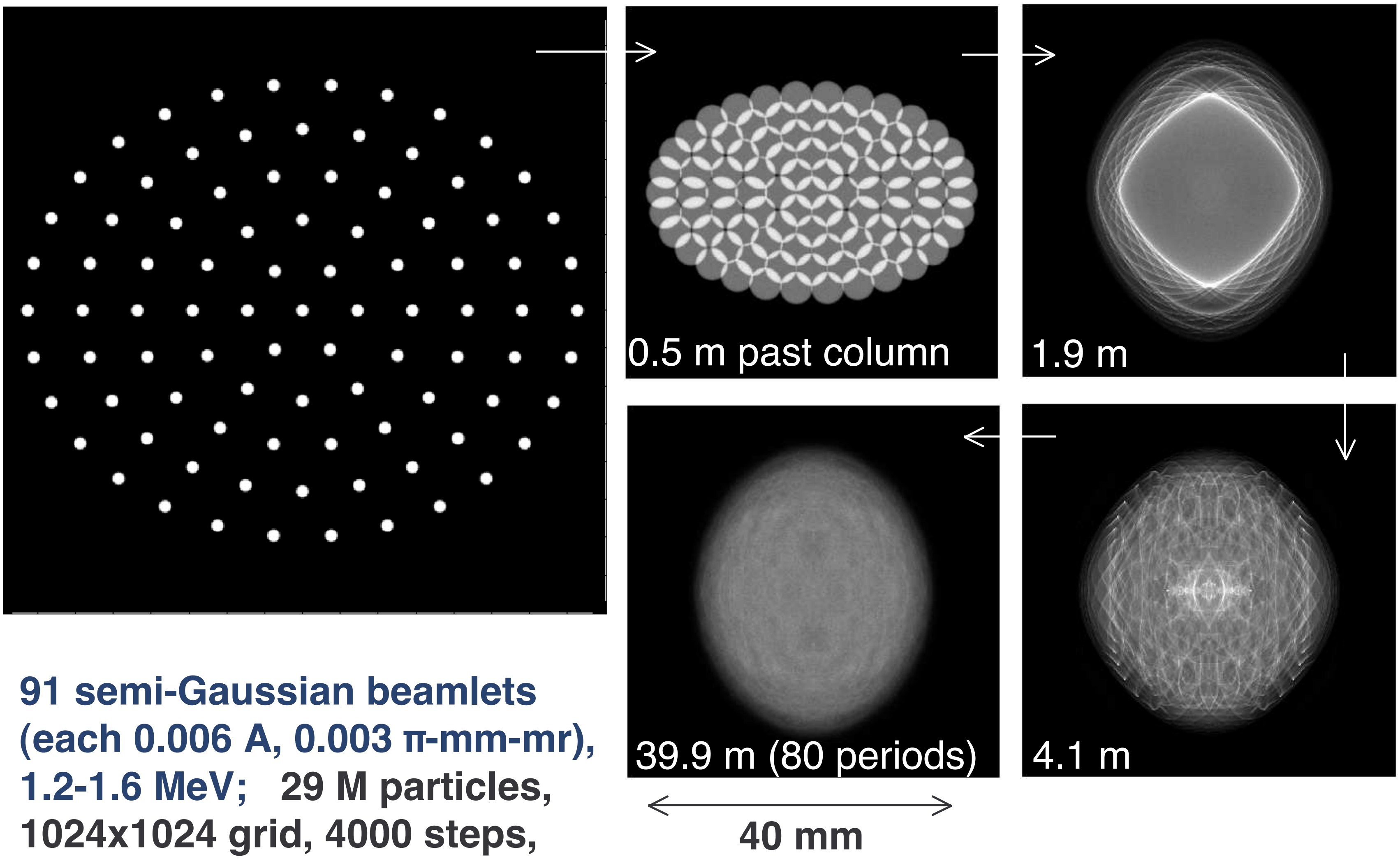
Areas to explore to enable ion-driven HED physics:

- **Beam-plasma effects in neutralized drift compression.**
- **Limits and control of incoherent momentum spread.**
- **Alternative focusing methods for high current beams, such as plasma lens.**
- **Foil heating (dE/dx measurements for low range ions < 10^{-3} g/cm^2) and diagnostic development.**

Simulation relevant to NDCX-I accel /decel experiment: Injected 2μs parabolic pulse, 25 mA, 10 keV, K⁺ beam, accelerated by a constant 200 kV/m (0 to1.5 m, after loading). (E. Henestroza 11-14-03)



2-D WARP simulation of multi-beamlet merging in a novel approach to an ion injector



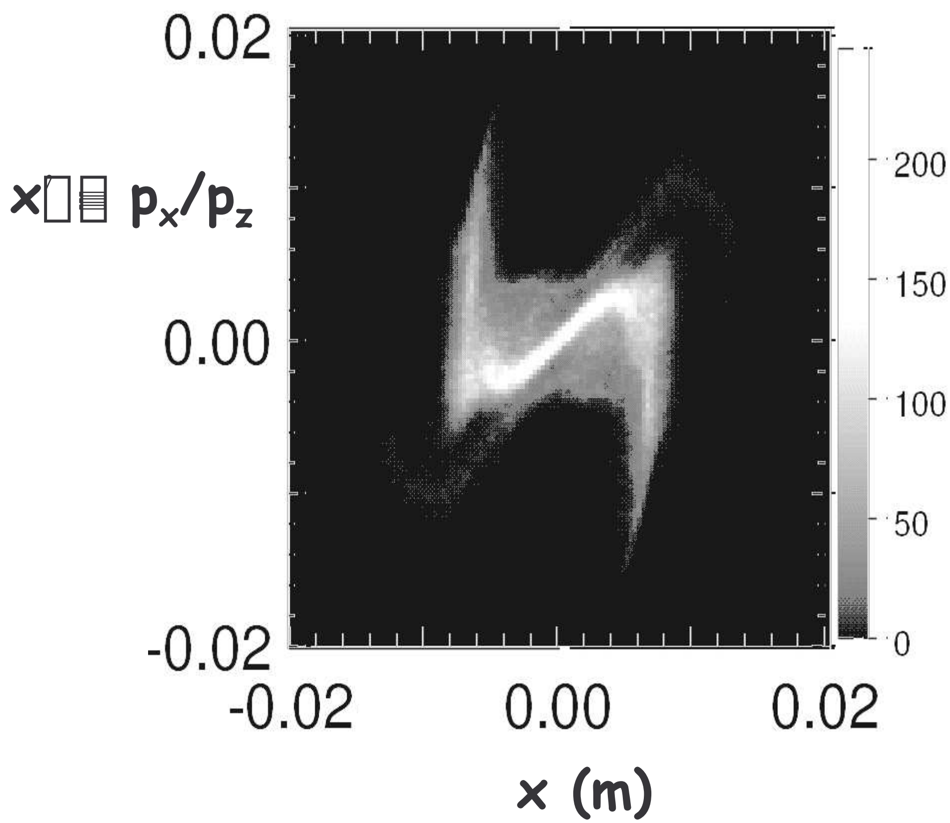
91 semi-Gaussian beamlets (each 0.006 A, 0.003 π-mm-mr), 1.2-1.6 MeV; **29 M particles, 1024x1024 grid, 4000 steps, 18.2 hrs on 64 IBM SP proc's**

(frames from a WARP movie by D. P. Grote)

Simulations of two injector approaches: similar emittances, qualitatively different phase spaces

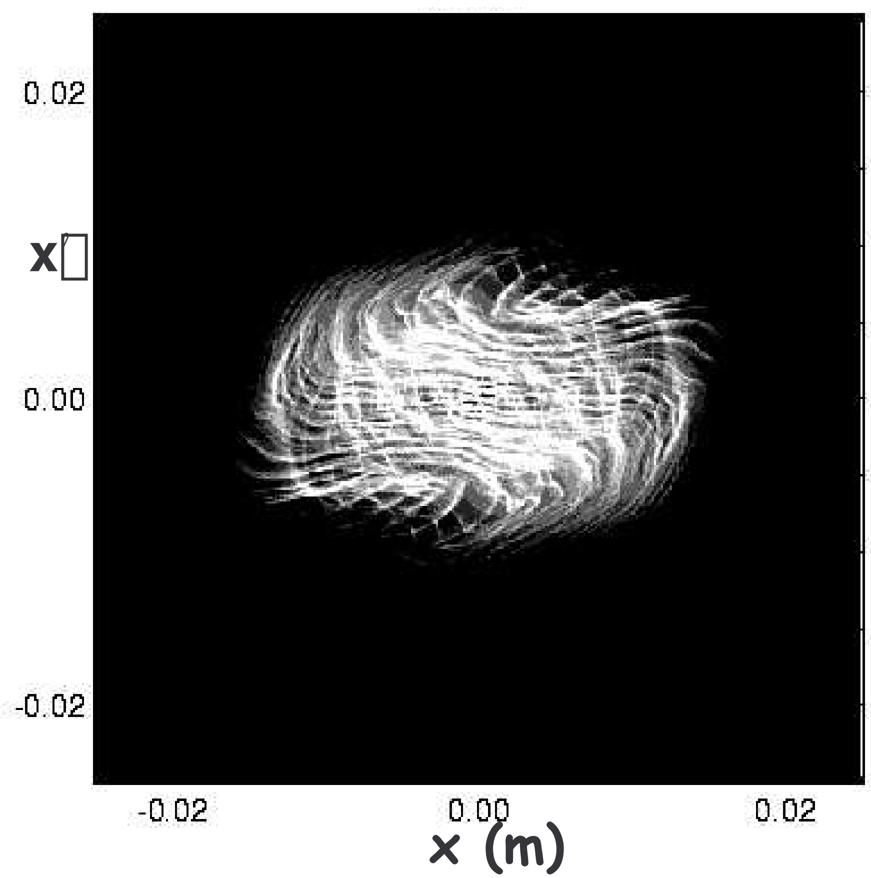
ESQ injector (555 mA)

(at end of matching section)

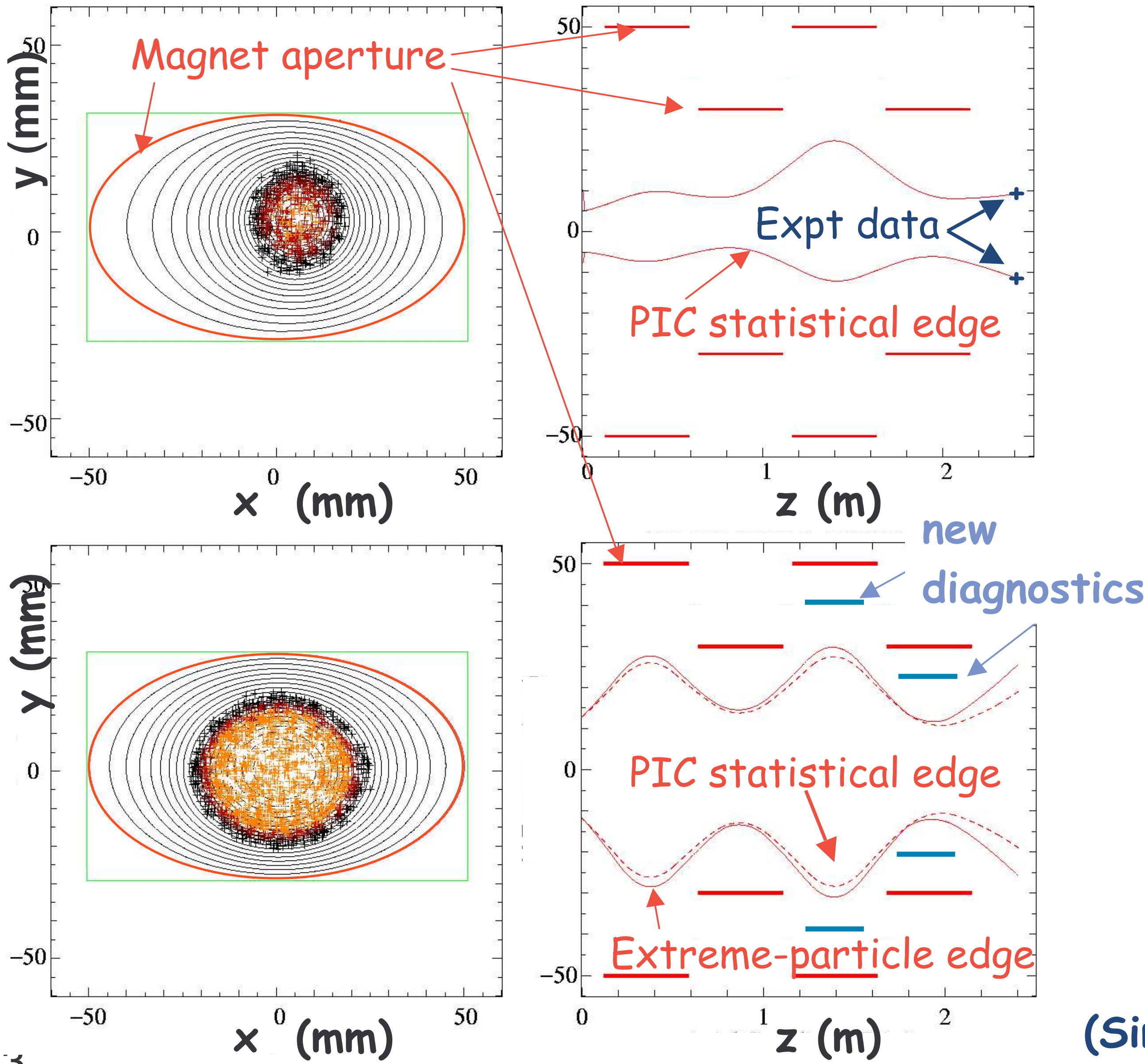


Merging-beamlets (572 mA)

(4.1 m past end of Pierce columns)



WARPxy 2D simulations initialized with measured (a,a,b,b) have been “workhorses” for HCX

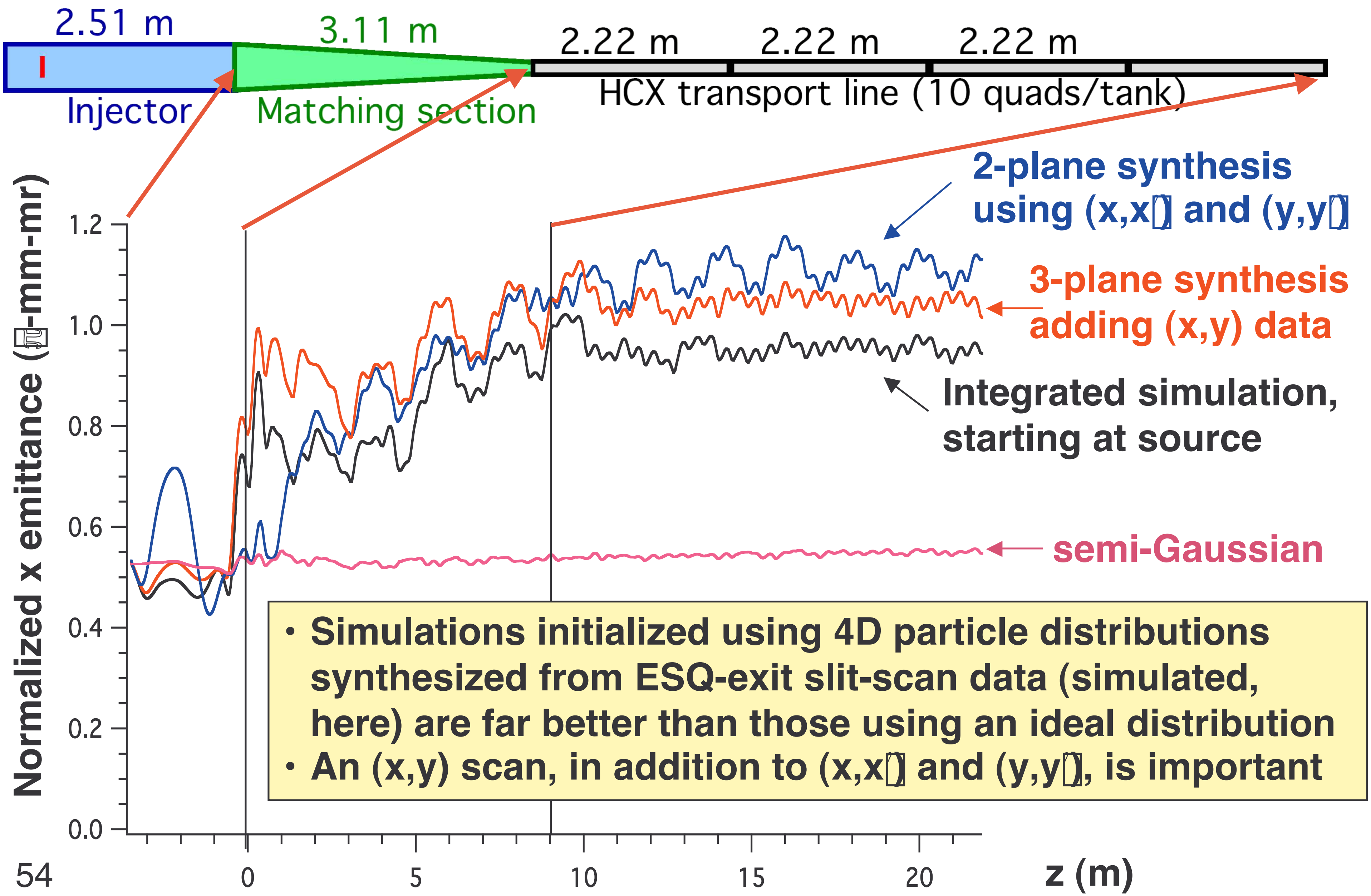


<u>32 mA beam</u>:
53% fill factor; good transport consistent with simulations

<u>175 mA beam</u>:
67% fill factor; recent experiments & simulations have been aimed at achieving clearance for diagnostics insertion

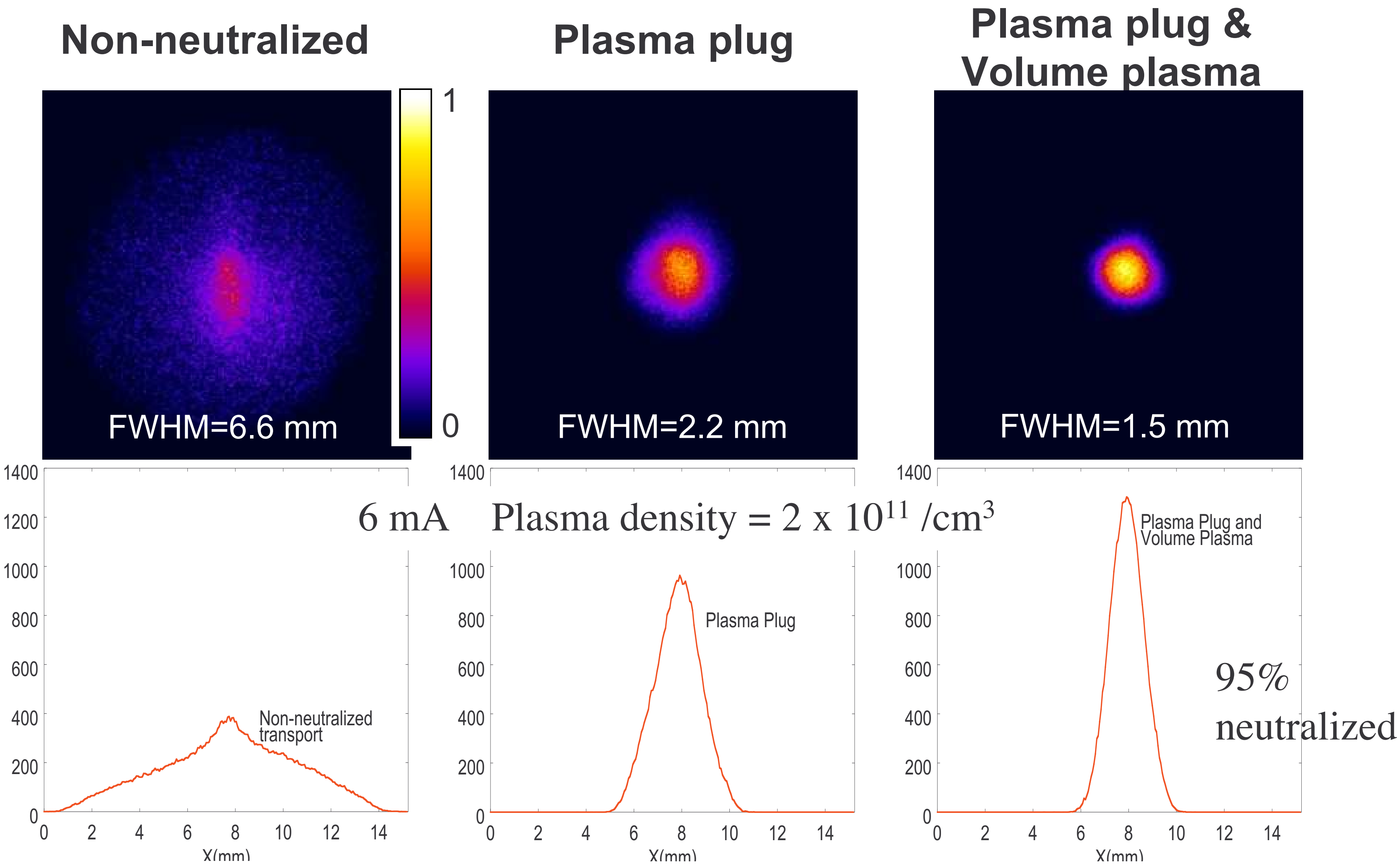
(Simulations by S. Lund)

We are using simulations to learn what data we need to take, and how best to use the data we obtain

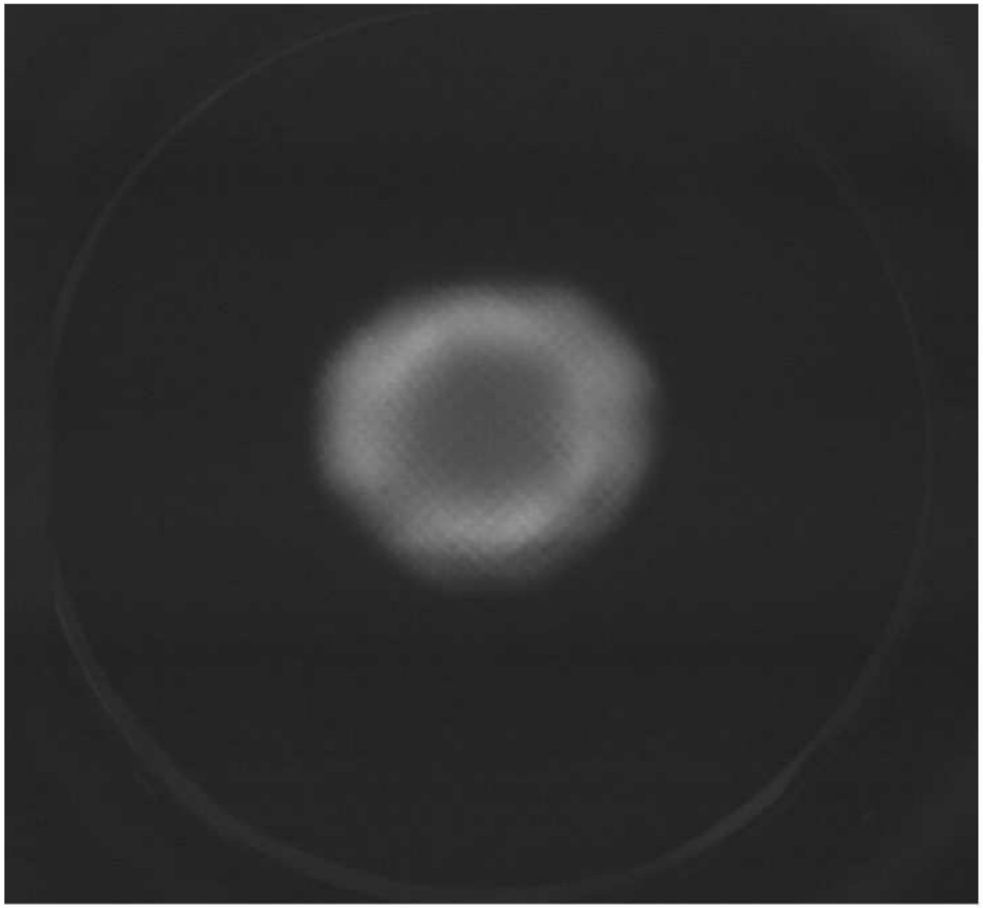


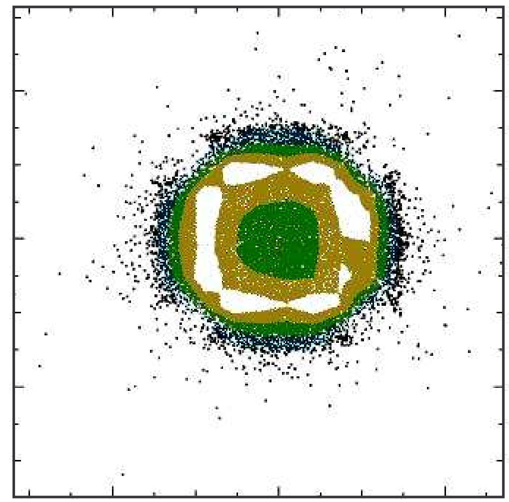
- Simulations initialized using 4D particle distributions synthesized from ESQ-exit slit-scan data (simulated, here) are far better than those using an ideal distribution
- An (x,y) scan, in addition to (x,x′) and (y,y′), is important

Reduction of spot size using plasma plug and volume plasma



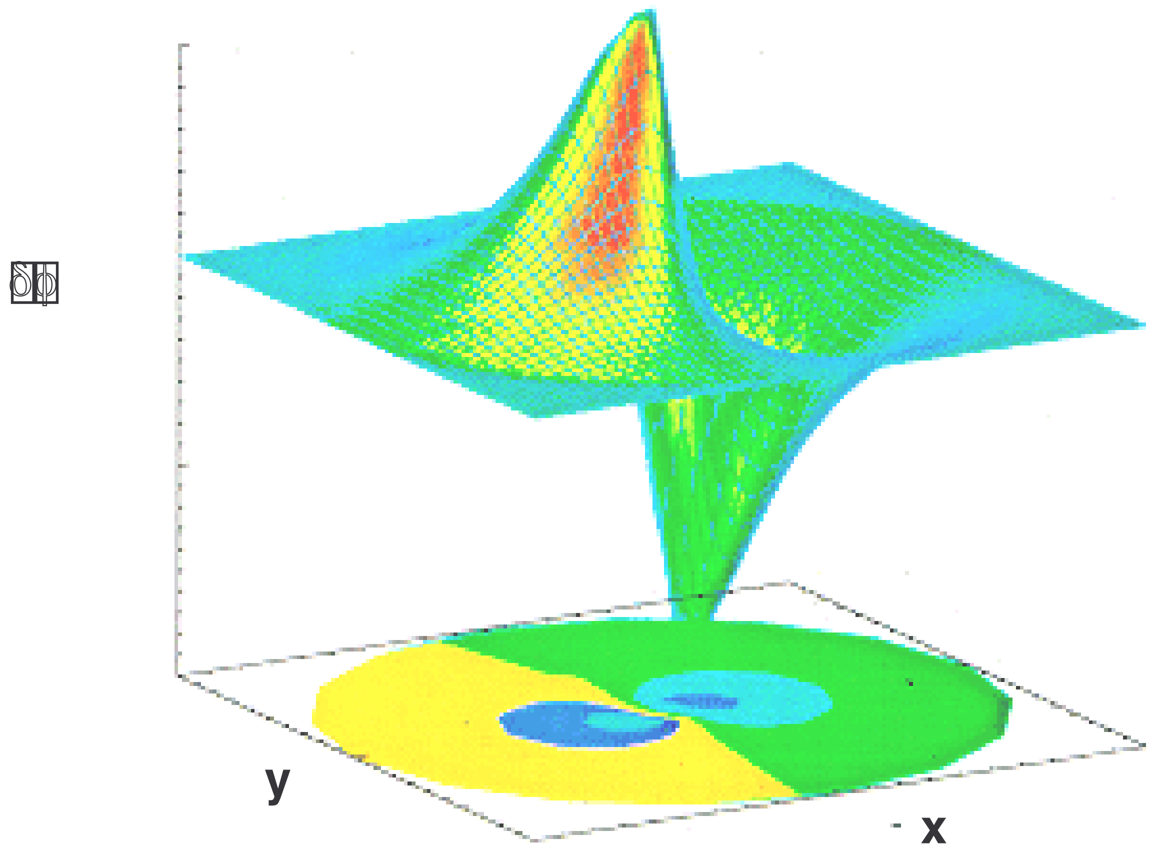
WARP simulations of the UMER electron gun reproduce some features of the observed velocity space





Beam velocity distribution emerging from the gun, measured as a phosphor screen image of the beam after passage through a small hole

(simulations by I. Haber / R. Kishek)



Nonlinear-perturbative BEST simulation of ion-electron two-stream instability reveals structure of eigenmode

Achieving HIF goals requires many processor-hours

- Source-to-focus WARP PIC simulation of a beam in a full-scale HIF driver
  - On Seaborg: key kernels achieve 700-900 Mflop/s single-processor; aggregated parallel performance is ~100 Mflop/s per processor
  - Observe good scalability up to 256 proc's on present-day problems; can assume further algorithmic improvements & larger problems
  - Next-step exp't (minimal): 440 proc-hrs (128x128x4096, 16M part's, 10k steps)
  - Full-scale system w/ electrons: 1.8 M proc-hrs (4x resolution, 4X longer beam, 4X longer path, two species, Δt halved, using new electron mover)
- While performance on the SP is comparable to that of other large codes, the SP architecture is not ideal for this class of problem
  - A higher fraction of peak parallel speed was achieved on T3E than SP
  - WARP should adapt especially well to a vector/parallel machine
  - Hardware gather and scatter valuable; scatter-add even more so
  - Trends toward multi-physics complexity and implicitness imply that benefits would accrue from easy programmability, flexibility, good parallel performance

Noteworthy progress in ion beam modeling is being made

- **Simulation studies in support of experiments:**
  - Injector science: large-aperture aberrations; short rise-time tests; multi-beamlet merging
  - HCX: WARP studies of transport & matching into magnetic quads; analysis of optical data
  - NTX: WARP and LSP studies of beam transport and focusing
- **Studies of future experiments**
  - Neutralized Drift Compression Experiments studying compression in space and time
  - simulation and analysis of HEDP-relevant beam experiments and modular driver approaches
  - time-dependent 3D simulations of a model IBX
  - scoping of scaled multi-beam experiment using electrons (with U. Md.)
- **Fundamental beam science studies**
  - electron cloud effects
  - quantitative assessment of effects of quadrupole magnet strength errors
  - "Harris" and "Weibel" anisotropy modes, and two-stream instability
  - drift compression and final focus (both non-neutral and neutralized), including solenoid focusing; time-dependent focusing; and chromatic aberration studies
  - beam aperturing and effects of beamline transitions
  - parametric limits to stable transport set by both envelope and kinetic effects
- **Development of advanced simulation capabilities**
  - Mesh refinement capability in WARP (application to injector triode, rise time study)
  - New Vlasov modeling methods: moving-mesh and "non-split" advance (with E. Sonnendrucker)
  - Large-timestep electron mover to allow computation on ion timescale